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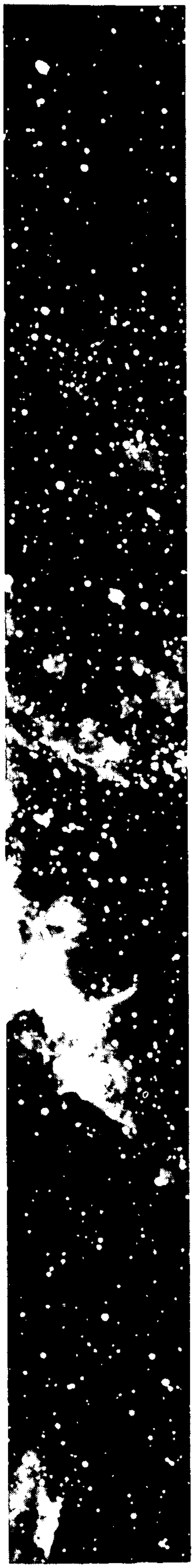
SPACE SYSTEMS



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LONG LIFE HIGH RELIABILITY THERMAL CONTROL SYSTEMS STUDY DATA HANDBOOK

PREPARED UNDER CONTRACT NAS 8-26252 BY

SPACE SYSTEMS ORGANIZATION
GENERAL ELECTRIC COMPANY
VALLEY FORGE SPACE TECHNOLOGY CENTER
POST OFFICE BOX 8555
PHILADELPHIA, PENNSYLVANIA 19101

FOR

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

DECEMBER 1971

CR-123734

GENERAL ELECTRIC

98

LONG LIFE HIGH RELIABILITY

THERMAL CONTROL SYSTEMS STUDY

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DATA HANDBOOK CONTENTS

Introduction

This Data Handbook has been prepared for Contract NAS 8-26252 undertaken by the General Electric Space Systems Organization for a "Long Life High Reliability Thermal Control Systems Study". The Handbook contains information on various passive and semi-active thermal control elements which have been flown (or considered for flight) on space vehicles.

A. Thermal Control Coatings

I. Purpose: The purpose of a thermal control coating is to provide a surface with known and desirable radiative properties. Specifically, coatings are utilized to obtain the values of solar absorptivity (α_s) and hemispherical emissivity (ϵ) required to maintain a favorable system thermal balance.

II. Types: Coatings flown on spacecraft to date have ranged from very simple (as received metallic surface) to very complex (optical solar reflector - OSR coatings). Many paints have been used, and special ones have been developed to obtain stable properties. Chemical surface finishes, such as alodine, anodize, flame and plasma spray have been applied to metallic components. Vapor deposition on metals and on flexible substrates has found extensive use. Front surface and second surface reflectors (series emittance) have been fabricated in tape form with adhesive backing.

Table A1 indicates methods of obtaining specific α_s and ϵ values. This table should be used in a general sense only, and should not be employed to obtain specific design properties. These values can be found on the data sheets presented in this section.

III. Properties: Certain coating properties are best presented by grouping the specific items into various classes. Table A2, for example, shows the temperature limit for various coating groups. Cost and weight data is shown in the same manner in Table A3, but it should be realized that exact figures depend on specific application.

TABLE A1

OBTAINABLE α_s AND ϵ FOR VARIOUS COATING TECHNIQUES

OPTICAL TYPE OF SURFACE	α_s	ϵ	Polished metals	"As Received" metals	"Sandblasted" metals	Vacuum metallics	Vacuum nonmetallics	Conversion coatings	Plated coatings	Metallic paints	Nonmetallic paints	Vitreous enamel	Inorganic bonded	Transparent conversion	Transparent nonpigmented paints
Total Absorber	.9	.9	--	--	--	--	--	X	--	--	X	X	X	X	X
Median I.R. Absorber	.9	.5	--	--	--	--	X	X	--	--	--	--	--	X	X
Solar Absorber	.9	.1	--	--	--	X	X	--	X	--	--	--	--	--	--
Median Solar Absorber	.5	.9	--	--	--	--	--	X	--	--	X	X	X	X	X
Medium	.5	.5	--	--	X	--	X	X	--	X	--	--	X	X	X
Median Solar Absorber	.5	.1	X	X	X	X	X	--	X	--	--	--	--	--	--
Solar Reflector	.1	.9	--	--	--	--	--	X	--	--	X	X	X	X	X
Median I.R. Reflector	.1	.5	--	--	--	--	X	X	--	X	--	--	--	X	X
Total Reflector	.1	.1	X	X	--	X	X	--	X	--	--	--	--	--	--

Reference: A18

TABLE A2

MAXIMUM TEMPERATURES FOR COATING GROUPS

Description	T Max., °F
Bare Metal	N/A
Paint	
Urethane Vehicle	150
Epoxy Vehicle	300
Silicone-alkyd Vehicle	650
Silicone Vehicle	800
Chemical Surface Finish	
Alodine (Conversion coating)	400
Anodize	1000
Flame, Plasma Spray	1000
Tapes	
Aluminized mylar	200
Series Emittance	800
Optical Solar Reflector (OSR)	600

Reference: A14

TABLE A3

RELATIVE COST AND WEIGHT FOR COATINGS

Description	Weight, Lbs/Sq Ft	Cost, $/Sq Ft
Bare Metal	0	0
Paints	.04	1-3
Chemical Surface Finishes	.03-.06	1-3
Tapes		
Aluminized Teflon	.06	4
Series Emittance	.06	4-5
Optical Solar Reflector (OSR)	.09	500

Reference: A2

Series emittance tapes can exhibit a wide α_s/ϵ range depending on overcoat thickness. Figure A1 shows obtainable ratios for four such tapes. These curves were prepared by fairing between empirically determined data points.

IV. Problems/Failure: Coatings can only completely fail by removal from the treated surface. Proper quality control techniques will prevent this occurrence. Performance can be degraded, however, from design values by time and by exposure to a hostile environment. Analytical techniques attempting to predict degradation have largely failed, so that laboratory simulation and flight performance comprise the majority of data available. The accuracy obtained in laboratory estimates of α_s degradation is dependent on the user's ability to predict and model the radiation and particulate environment that the coating will be exposed in space.

The degradation of coatings with low initial values of α_s/ϵ is of prime interest to thermal engineers. These coatings are generally used on space radiators which reject vehicle heat. Increases in α_s with time raises vehicle temperature, and can lead to equipment failure. Figure A2 was prepared from selected flight data to indicate the relative degradation of often-used low α_s/ϵ coatings.

V. Advances: Reference A19 considers several conceptual coating systems which exhibit temperature - dependent absorptivity characteristics. The interest in these systems is apparent when it is realized that active thermal control can be obtained with essentially passive components.

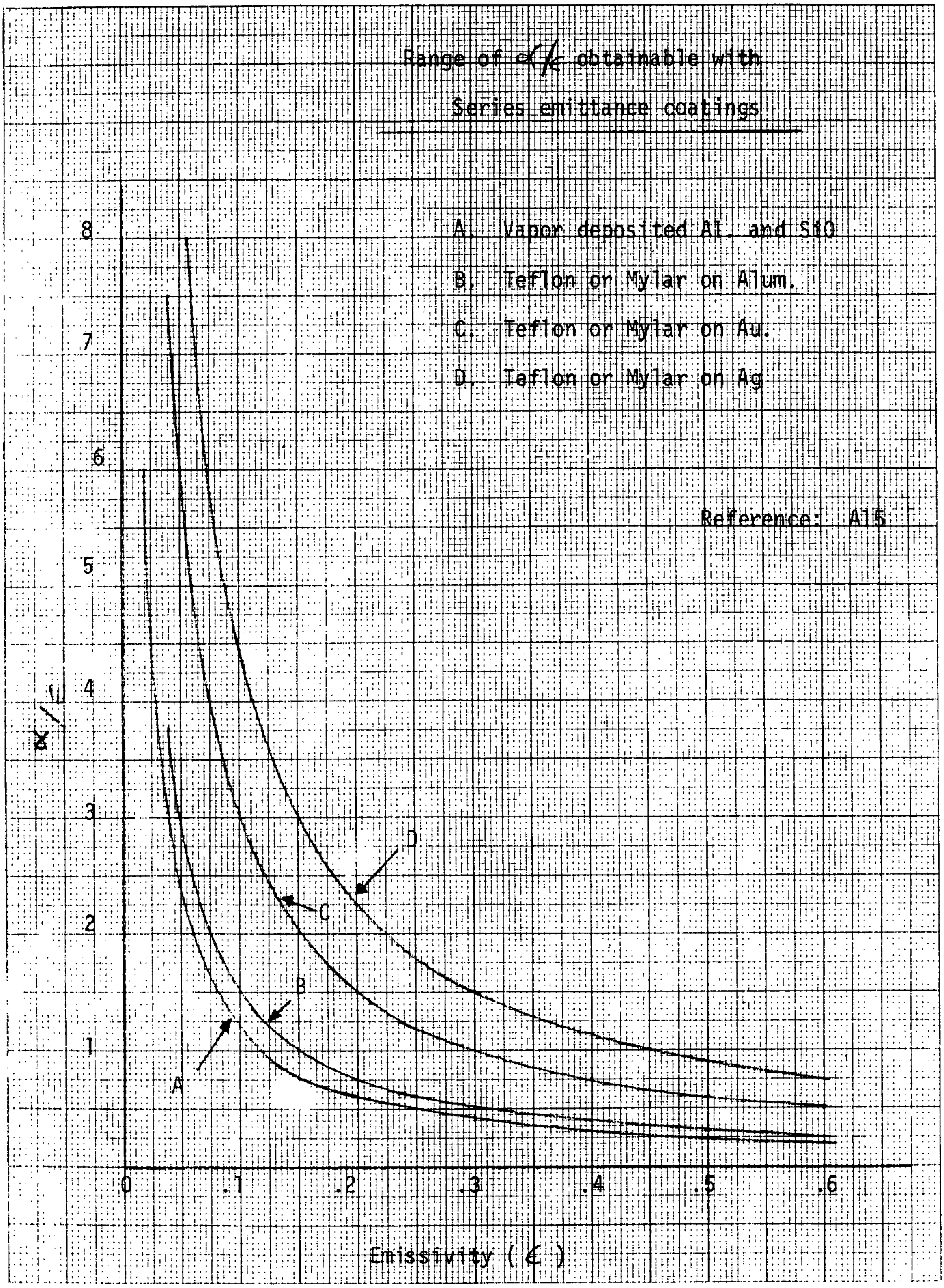

Range of α/ε obtainable with
Series emittance coatings
A. Vapor deposited Al. and SiO
B. Teflon or Mylar on Alum.
C. Teflon or Mylar on Au.
D. Teflon or Mylar on Ag
Reference: A15
α/ε
8
7
6
5
4
3
2
1
0
.1
.2
.3
.4
.5
.6
A
B
C
D
Emissivity (ε)

FIGURE A1

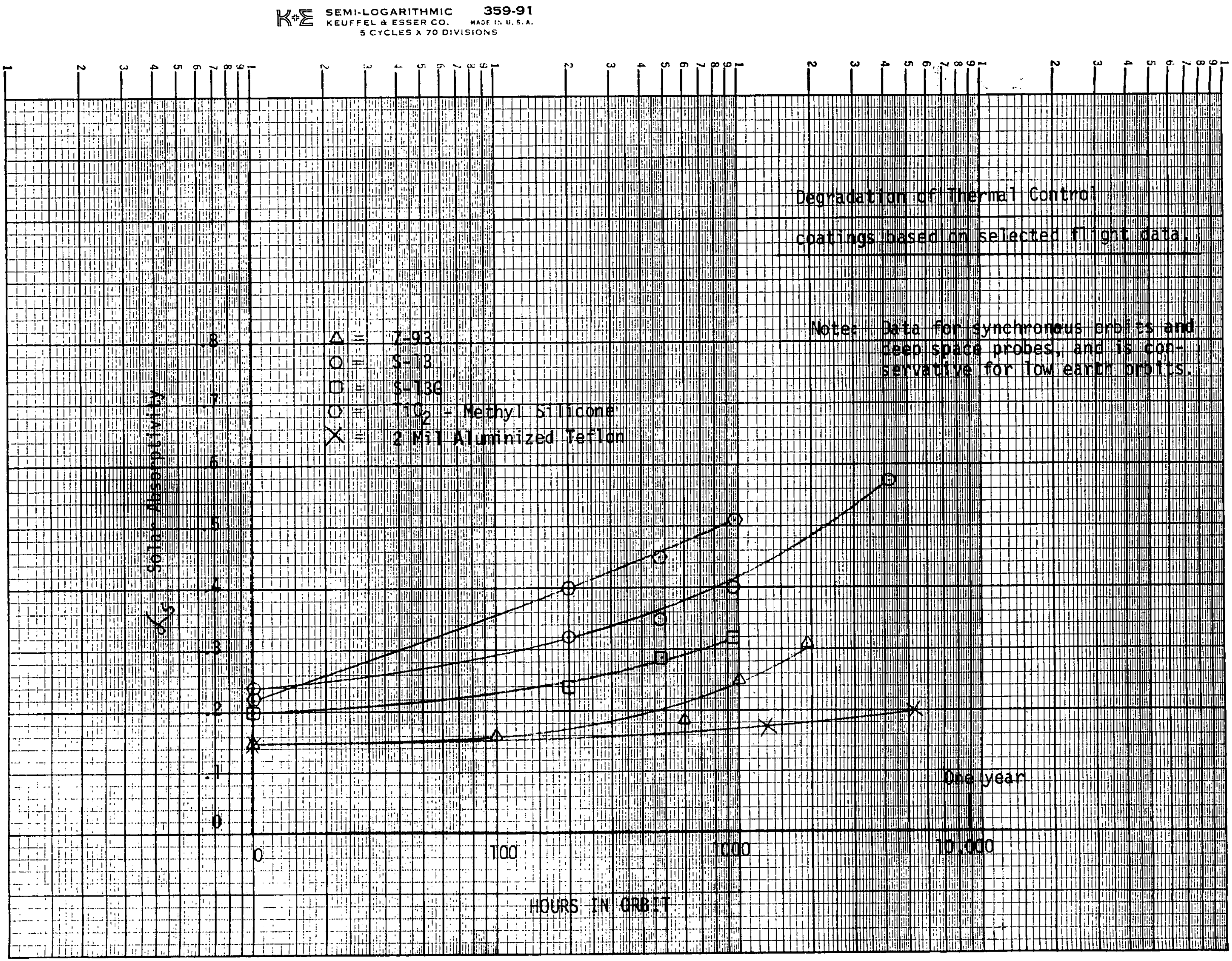

K+E SEMI-LOGARITHMIC 359-91
KEUFFEL & ESSER CO. MADE IN U.S.A.
5 CYCLES X 70 DIVISIONS
Degradation of Thermal Control coatings based on selected flight data.
Note: Data for synchronous orbits and deep space probes, and is conservative for low earth orbits.
△ = Z-93
○ = S-13
□ = S-13G
⬡ = TiO_2 - Methyl Silicone
X = 2 Mil Aluminized Teflon
Solar Absorptivity α_s
.8
.7
.6
.5
.4
.3
.2
.1
0
0
100
1000
10,000
One year
HOURS IN ORBIT

FIGURE A2
A-7

Analytical and empirical results reported are somewhat encouraging, but more development is necessary in this area.

VI. Data Sheets: The data sheets that follow present properties for specific coatings. The sheets are self-explanatory with two exceptions. "BOL" means beginning of life value, and "EUVSH" means equivalent ultraviolet sun hours.

Reference A20 presents an excellent discussion of degradation/contamination effects on coatings considered for space station application. A review of this reference is recommended to those requiring more detailed information on long-term absorptance changes than is presented in this Handbook.

THERMAL CONTROL COATINGS

Low α_s / ϵ (< .4)

NO.	Classi-cation	Desig-nation	DESCRIPTION	BOL α_s	BOL ϵ	α_s/ϵ	$\Delta\alpha_s$	DOSAGE	FLOWN ON	REF.	COMMENTS
1	Paint	Z - 93	Z_nO in K_2SiO_3	.17	.90	.19	.01 .13	100 EUVSH 3000 EUVSH	OSO, Mariner	A1	Brittle, hard to apply and maintain.
2	Paint	S - 13	Z_nO in methyl silicone vehicle	.23	.85	.27	.04 .20 .20	200 EUVSH (in lab) 20 days in orbit (Pegasus) 48 days in orbit (Mariner)	Pegasus, Lunar Orbiter Mariner V	D1, A7	Rocket exhaust may have contaminated coating on Pegasus.
3	Paint	S - 13G	S_nO coated K_2SiO_3 in silicone vehicle painted over S-13	.21	.87	.24	.05 .21	900 EUVSH (in lab) 900 hrs. total flight time (Lunar Orbiter)	Lunar Orbiter	A10	
4	Paint	S- 13M		.20	.86	.23	.12	39 days in orbit	Mariner V	A7	
5	Paint	Vitavar PV 100	T_iO_2 filled silicone alkyd coating	.21 - .22	.86 - .88	.24 - .25	.08 .31	1 yr. EUV for low earth orbit (in lab) 1 yr. protons + electrons for low earth orbit (in lab)	Nimbus, GGTS Relay	A4	
6	Paint	Lockpaint	Organic Z_nO pigmented silicate based coating	.19 - .28	.95	.20 - .29				A4	Not tested for degradation.

THERMAL CONTROL COATINGS

Low α_s/ϵ (< .4)

NO.	Classi-cation	Desig-nation	DESCRIPTION	BOL α_s	BOL ϵ	α_s/ϵ	$\Delta\alpha_s$	DOSAGE	FLOWN ON	REF.	COMMENTS
7	Paint	MSD 105	Modification of Lockpaint	.19 - .23	.95	.20 - .24	.092	1 yr. protons + electrons for low earth orbit (in lab)		A4	
8	Paint	BFC 91-01	T_iO_2 pigmented polyurethane based coating	.25 - .27	.95	.28 - .30	.25 .235	1 yr. EUV for low earth orbit (in lab) 1 yr. protons + electrons for low earth orbit (in lab)		A4	
9	Paint	Pyromark Standard White		.20 - .26	.88 - .89	.20 - .31	.17 .07	1 yr. EUV for low earth orbit (in lab) 1 yr. protons + electrons for low earth orbit (in lab)	201, 206	A4	
10	Paint		$Z_nO-K_2SiO_3$	.20	.93	.22	.05 - .09	73 hrs. in low earth orbit	Apollo 9	A6	Degradation caused by deposition of outside contaminants.
11	Paint		T_iO_2 - Silicone	.24	.86	.28	.10 - .16	73 hrs. in low earth orbit	Apollo 9	A6	Same comment as above
12	Paint	C2A (M. A. Bruder)	T_iO_2 pigment in silicone and a-crylic resins	.19	.87	.22	.11 .20	100 EUVSH 1000 EUVSH	Classified military programs	A9, A10	

Low α_s/ϵ (<.4)

THERMAL CONTROL COATINGS

NO.	Classi-cation	Desig-nation	DESCRIPTION	BOL α_s	BOL ϵ	α_s/ϵ	$\Delta\alpha_s$	DOSAGE	FLOWN ON	REF.	COMMENTS
13	Paint	White Kem-acryl (Sherwin-Williams)	T_iO_2 pigment in acrylar vehicle	.28	.86	.33	.09 .01 .19	436 EUVSH Electrons (5 KEV, 6×10^7 rads) Above combined		A10	
14	Paint	Skyspar 423	T_iO_2 pigment in epoxy vehicle	.23	.85	.27	.23	1.5 yrs. in low earth orbit	OSO I	A10	
15	Paint		T_iO_2 pigment in silicone	.27	.76	.35	.13	1.5 yrs. in low earth orbit	OSO I	A10	
16	Paint	Rutile	T_iO_2 pigment in methyl-silicone vehicle	.23	.85	.27	.18	1.3 yrs in orbit	Pegasus	A10	
17	Paint		White porcelan enamel. Alkali T_iO_2 in boro-silicate glass.	.25	.75	.33	.05	3000 sun hours in orbit	OSO I	A10	
18	Second Surface Reflector	OSR (optical solar reflector)	~1000 Å silver, then 500 Å inconel vapor deposited over corning 7940 Fused silica	.05	.76	.07	.005	1580 ESH in low earth orbit	OSO III	A1	

THERMAL CONTROL COATINGS

Low α_s/ϵ ($<$ .4)

NO.	Classi-cation	Desig-nation	DESCRIPTION	BOL α_s	BOL ϵ	α_s/ϵ	$\Delta\alpha_s$	DOSAGE	FLOWN ON	REF.	COMMENTS
19	Plasma Spray		Al_2O_3	.21	.80	.26	.05	7.5 mos. in orbit	Telstar I	A10	
20	Flame Spray	Rokide A	Al_2O_3	.27	.75	.36	0.0	1000 EUV SH in lab		A15	
21	Second Surface Reflector	Schjeldahl G-107300 tape	Vapor deposited Aluminum and SiO on 1 mil kapton	.09 - .13		.19 - .31				A16	
22	Second Surface Reflector	Series Emittance tape	FEP Teflon over aluminum. Teflon thickness = .5mil = 1 mil = 2 mils = 5 mils =10 mils	.13 .12 .13 .17 .21	.43 .53 .67 .83 .89	.30 .23 .19 .20 .24	0.0 .07	180 EUVSH plus 4 x 10^6 rads x-ray 51 EUVSH plus 1.5 x 10^{16} protons/cm^2 at 3 KEV		A11 A12	
23	Second Surface Reflector	Series Emittance tape	FEP Teflon over silver. Teflon thickness = .5 mils = 1 mil = 2 mils = 5 mils	.055 .059 .059 .090	.42 .52 .68 .82	.13 .11 .087 .11	0.0	180 EUVSH plus 4 x 10^6 rads x-ray		A12 A13	

THERMAL CONTROL COATINGS

Low α_s/ϵ (< .4)

NO.	Classi- cation	Desig- nation	DESCRIPTION	BOL α_s	BOL ϵ	α_s/ϵ	$\Delta\alpha_s$	DOSAGE	FLOWN ON	REF.	COMMENTS
24	Second Surface Reflector	Series Emittance Tape	Butvar (Polyvinyl butyral) over aluminum. Butvar thickness = .75 mil	.18	.45	.40				A12, A13	
			=3.2 mils	.22	.85	.26					
			=6.5 mils	.22	.88	.25					
			=8.0 mils	.17	---	---	0.0	250 EUVSH			
							.25	70 EUVSH plus 2.1×10^{16} proton/cm^2 at 4 KEV			

Mid α_s/ϵ (.4 ◄ ► 1.1)

THERMAL CONTROL COATINGS

NO.	Classi-cation	Desig-nation	DESCRIPTION	BOL α_s	BOL ϵ	α_s/ϵ	$\Delta\alpha_s$	DOSAGE	FLOWN ON	REF.	COMMENTS
25	Paint	3M Velvet Black (104C-10)	Thickness = 4mils	.968	.923	1.05	0.0	100 EUVSH		A3	
26	Paint	Pyromark Black	Silicone Alkyd paint	.92	.87	1.06				A9	
27	Paint	Pyromark Gray	Silicone Alkyd paint blended from Pyromark white and black paints	.22 - .92	.90	.3 - 1.1	.05 - .20	1000 EUVSH		A15	
28	Paint	Parsons Black		.98	.96	1.02			OAO	A9	Poor handling and durability
29	Paint	D4D	Aluminum leaf pigment in silicone alkyd vehicle	.26	.28	.93	.07	2160 EUVSH in low earth orbit	NRL, GEOS, Nimbus, Discoverer	A9, A10	Extremely stable to environmental exposure
30	Paint	C6A (M. A. Bruder)	Carbon black pigment in silicone and acrylic resins	.92	.96	.96	0.0	1000 EUVSH	Classified military programs	A9	
31	Paint	C2A-C6A (M. A. Bruder) Gray	T_iO_2-Carbon black pigments in silicone and acrylic binder	.20 - .90	.80 - .90	.25 - .94				A10	

Mid α_s / ϵ (.4 ⟷ 1.1)

THERMAL CONTROL COATINGS

NO.	Classi-cation	Desig-nation	DESCRIPTION	BOL α_s	BOL ϵ	α_s / ϵ	$\Delta\alpha_s$	DOSAGE	FLOWN ON	REF.	COMMENTS
32	Paint	Cat-a-lac Black	Carbon black pigment in epoxy vehicle	.94	.94	1.00	-.03	2400 flight hours	Mariner V	A10 A7	Apparent bleaching of coating
33	Paint	PD 114 (Gray)	T_iO_2-Carbon black pigments in baked silicone binder	.25 - .80	.90	.30 - .95	.05 - .15	1000 flight hours	Classified military programs	A10 A15	
34	Paint		Aluminum leaf pigment in silicone vehicle	.26	.26	1.00	0.0	1.5 yrs. in orbit	OSO I	A10	
35	Paint		Aluminum leaf pigment in silicone vehicle	.25	.26	.96	0.0	2.2 yrs. in orbit	Mariner IV	A10	
36	Paint	Epoxy flat black	GE Spec. 171A4400	.94	.90	1.04	0.0	1000 EUVSH		A15	
37	Paint	Lowes 47854	(Black) Glyceral-Phthalate		.904					A15	
38	Chemical Surface Finish	Dow 23		.67	.79	.85				A5	On magnesium

Mid α_s/ϵ (.4 ⟷ 1.1)

THERMAL CONTROL COATINGS

NO.	Classi-cation	Desig-nation	DESCRIPTION	BOL α_s	BOL ϵ	α_s/ϵ	$\Delta\alpha_s$	DOSAGE	FLOWN ON	REF.	COMMENTS
39	Chemical Surface Finish		Chromic acid anodized aluminum	.70	.73	.96	.03	73 hrs. in low earth orbit	Apollo 9	A6	Degradation caused by deposition of outside contaminants
40	Chemical Surface Finish	Black Anodize, GE Spec 171A4227	Carbon black impregnated anodize coating		.90					A10	On aluminum
41	Vapor Deposition		Gold on kapton	.41	.81	.51	0.0	1000 EUVSH		A10	Data is for kapton surface
42	Vapor Deposition	Schjeldahl G-107600	Aluminum on 1 mil kapton	.32 max.	.75 max.	.42 max.				A16	Data is for kapton surface
43	Second Surface Reflector	Schjeldahl G-101500 Tape	Aluminum + SiO on .5 mil kapton		.42 max.	.35 - .45			Apollo Command Module	A16	Data is for metallic surface. Silicone pressure sensitive adhesive.
44	Second Surface Reflector	Schjeldahl G-101701 Tape	Vapor deposited aluminum and SiO on .5 mil kapton	.10 - .16	.11 - .21	.70 - 1.0				A16	Same comment as above.
45	Second Surface Reflector	Schjeldahl G-101600 Tape	Vapor deposited aluminum and SiO on .5 mil kapton		.06 - .14	1.0 - 1.2				A16	Same comment as above

Mid α_s/ϵ (.4 → 1.1)

THERMAL CONTROL COATINGS

NO.	Classi-cation	Desig-nation	DESCRIPTION	BOL α_s	BOL ϵ	α_s/ϵ	$\Delta\alpha_s$	DOSAGE	FLOWN ON	REF.	COMMENTS
46	Second Surface Reflector	Schjeldahl G-101801 Tape	Vapor deposited aluminum and SiO on 4 mil aluminum foil	.20 - .30	.22 - .34	.70 - 1.0				A16	Data is for metallic surface. Silicone pressure sensitive adhesive.
47	Second Surface Reflector	Schjeldahl G-101802	Vapor deposited aluminum and SiO on 4 mil aluminum foil	.23 - .33	.50 - .62	.40 - .60				A16	Same comment as above.
48	Second Surface Reflector	Schjeldahl G-101901	Vapor deposited aluminum and SiO on 1 mil kapton	.12 - .18	.14 - .22	.70 - 1.0				A16	Data for metallic surface. Acrylic pressure sensitive adhesive.
49	Second Surface Reflector	Schjeldahl G-101902 Tape	Vapor deposited aluminum and SiO on 1 mil kapton	.09 - .14	.28 - .37	.32 - .48				A16	Same comment as above.
50	Second Surface Reflector	Schjeldahl G-102000 Tape	Vapor deposited aluminum on .5 mil kapton plus nylon tulle	.12 - .16	.13 - .17	.70 - 1.2				A16	Same comment as above.

High α_s/ϵ (>1.1)

THERMAL CONTROL COATINGS

NO.	Classi-cation	Desig-nation	DESCRIPTION	BOL α_s	BOL ϵ	α_s/ϵ	$\Delta\alpha_s$	DOSAGE	FLOWN ON	REF.	COMMENTS
51	Bare Metal	Aluminum	Polished	.15	.04	3.75				A17	
52	Bare Metal	Gold	Polished	.21	.02	10.5				A17	
53	Bare Metal	Magnesium	Polished	.27	.07	3.9				A17	
54	Bare Metal	Stainless Steel	Polished	.20	.09	2.2				A17	
55	Bare Metal	Silver	Polished	.07	.02	3.5				A17	
56	Bare Metal	Titanium	Polished	.51	.08	6.4				A17	
57	Vapor Deposition	Schjeldahl G-103300 Tape	Aluminum on 1 mil kapton	.13 max.	.05 max.					A16	Data for metallic side. Silicone pressure sensitive adhesive
58	Vapor Deposition	Schjeldahl G-103500 Tape	Aluminum on .5 mil kapton	.10 - .14	.06 max.	1.7 - 2.3				A16	Same comment as above.

High α_s / ϵ (> 1.1)

THERMAL CONTROL COATINGS

NO.	Classi-cation	Desig-nation	DESCRIPTION	BOL α_s	BOL ϵ	α_s/ϵ	$\Delta\alpha_s$	DOSAGE	FLOWN ON	REF.	COMMENTS
59	Vapor Deposition		Aluminum on mylar	.13	.024	5.4	0.0	1000 EUVSH	As insulation on many space-craft	A10	Data for metallic side
60	Vapor Deposition		1000-2000 Å alumi-num on unspecified surface	.08	.014	5.7				A9	Polished surface. Measured in vacuum
61	Vapor Deposition		Same as above	.15	.051	2.9				A9	Polished surface. Measured in air
62	Vapor Deposition		1000-2000 Å Gold on unspecified surface	.192	.014	13.7				A9	Polished surface. Measured in vacuum.
63	Vapor Deposition		Same as above	.30	.14	2.1				A9	Polished surface. Measured in air.
64	Vapor Deposition		1000-2000 Å Copper on unspecified surface	.172	.014	12.3				A9	Polished surface. Measured in vacuum
65	Vapor Deposition		Same as above	.45	.01 - .08	5.6 - 45.				A9	Polished surface. Measured in air.
66	Vapor Deposition (protected)		2000 Å of gold with 1000 Å SiO overcoat	.206	.03	6.9				A8	On mill finish aluminum

High α_s/ϵ (>1.1)

THERMAL CONTROL COATINGS

NO.	Classi-cation	Desig-nation	DESCRIPTION	BOL α_s	BOL ϵ	α_s/ϵ	$\Delta\alpha_s$	DOSAGE	FLOWN ON	REF.	COMMENTS
67	Vapor Deposition (protected)		2000 Å of gold with 1000 Å Al_2O_3	.215	.04	5.4	0.0	250 EUVSH		A8	On mill finish aluminum
68	Vapor Deposition (protected)		2000 Å of aluminum with 1000 Å SiO overcoat	.184	.06	3.1	0.0	250 EUVSH		A8	Same comment as above.
69	Vapor Deposition (protected)		2000 Å of aluminum with 1000 Å Al_2O_3 overcoat	.163	.07	2.3	0.0	250 EUVSH		A8	Same comment as above.
70	Vapor Deposition (protected)		2000 Å of silver with 1000 Å of SiO overcoat	.085	.04	2.1	0.0	250 EUVSH		A8	Same comment as above
71	Vapor Deposition (protected)		2000 Å of silver with 1000 Å of Al_2O_3 overcoat	.105	.04	2.6	0.0	250 EUVSH		A8	Same comment as above.
72	Vapor Deposition (protected)		Vapor deposited aluminum with alumina overcoat	.12	.03 - .50	.24 - 4.0	.03	Protons - 200 KEV 5×10^9 rads		A10	ϵ controlled by varying Al_2O_3 thickness.
73	Vapor Deposition (protected)		Vapor deposited aluminum with silica overcoat	.10	.04	2.5	.07	6000 EUVSH plus electrons (5 KEV, 6×10^7 rads)		A10	No thickness of SiO given

High α_s/ϵ (>1.1)

THERMAL CONTROL COATINGS

NO.	Classi-cation	Desig-nation	DESCRIPTION	BOL α_s	BOL ϵ	α_s/ϵ	$\Delta\alpha_s$	DOSAGE	FLOWN ON	REF.	COMMENTS
74	Chemical Surface Finish	Alodine 401-41	Bath temperature = 28°F =118°F =201°F	.331	.041 .046 .046	7.12				A18	On aluminum. Immersion time (I) = 15 sec.
75	Chemical Surface Finish	Alodine 401-41	Bath temperature = 37°F =135°F =207°F	.357	.059 .059 .070	6.05				A18	On aluminum, I = 30 sec.
76	Chemical Surface Finish	Alodine 401-41	Bath temperature = 32°F =111°F =205°F	.343	.070 .082 .087	4.18				A18	On aluminum. I = 60 sec.
77	Chemical Surface Finish	Alodine 401-41	Bath temperature = 36°F =117°F =203°F	.349	.149 .158 .156	2.21				A18	On aluminum. I=120 sec.
78	Chemical Surface Finish	Alodine 401-41	Bath temperature = 28°F =129°F =205°F	.335	.159 .180 .181	1.86				A18	On aluminum. I = 180 sec
79	Chemical Surface Finish	Alodine 401-41	Bath temperature = 30°F =122°F =198°F	.347	.202 .262 .252	1.32				A18	On aluminum. I = 240 sec

THERMAL CONTROL COATINGS

High α_s/ϵ (> 1.1)

NO.	Classi-cation	Desig-nation	DESCRIPTION	BOL α_s	BOL ϵ	α_s/ϵ	$\Delta\alpha_s$	DOSAGE	FLOWN ON	REF.	COMMENTS
80	Chemical Surface Finish	Alodine 401-41	Bath temperature = 28°F =122°F =199°F	.414	.506 .506 .506	.82				A18	On aluminum. I = 540 sec
81	Chemical Surface Finish	Alodine 600		.57	.09	6.3				A5	On aluminum. No details given.
82	Chemical Surface Finish	Alodine 1200S	Bath temperature = 43°F =136°F =194°F	.395	.047 .046 .046	8.59				A18	On aluminum. I = 30 sec
83	Chemical Surface Finish	Alodine 1200S	Bath temperature = 36°F =126°F =199°F	.432	.043 .052 .049	8.31				A18	On aluminum. I = 60 sec.
84	Chemical Surface Finish	Alodine 1200S	Bath temperature = 23°F =135°F =208°F	.480	.070 .064 .061	7.50				A18	On aluminum. I =120 sec
85	Chemical Surface Finish	Alodine 120CS	Bath temperature = 36°F =124°F =207°F	.487	.077 .070 .073	6.96				A18	On aluminum. I =300 sec
86	Chemical Surface Finish	Alodine 1200S	Bath temperature = 39°F =115°F =196°F	.488	.101 .094 .094	5.19				A18	On aluminum. I =480 sec.

B. Insulation

I. Purpose: Thermal insulation is employed to decouple a surface from its environment. Ideally, insulation structures should provide infinite thermal resistance to heat flow by conduction, convection and radiation.

II. Types: Several types of thermal insulation systems have been studied for space application. Foams, powders, fibers, and multilayer radiation barriers have been empirically evaluated in vacuum. Figure B.1 presents observed results in the form of equivalent thermal conductivity ranges for each system. This data is applicable for hot surfaces at about $60^{o}F$ and sinks of about $-320^{o}F$, which are typical in spacecraft design.

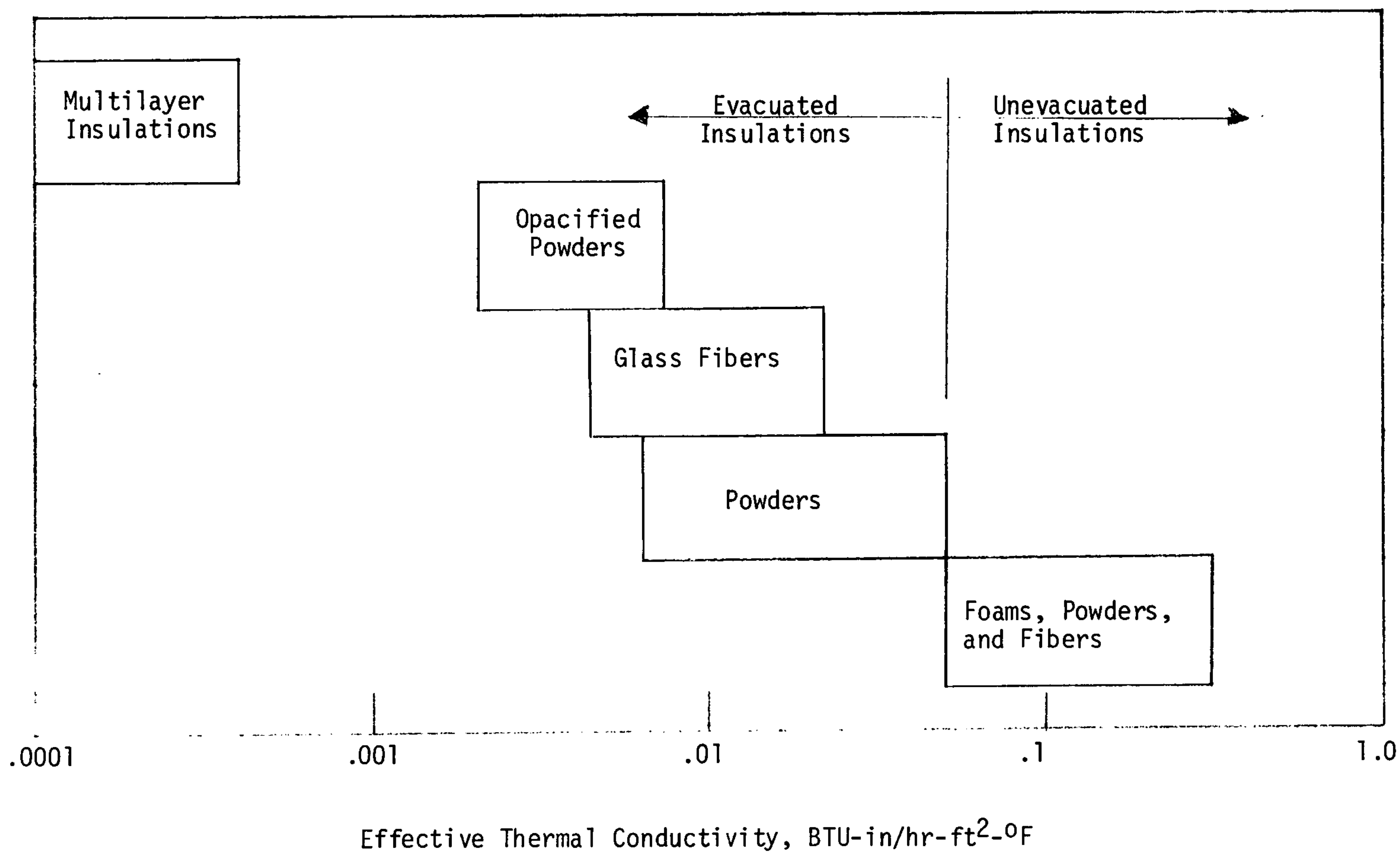
As can be seen on Figure B.1, multilayer insulations offer at least an order of magnitude improvement in performance over the second best class, opacified powders. Therefore, multilayer systems have received the majority of attention in this area.

Multilayer systems made of flexible films (both with and without interlayer spacers) are called multilayer insulation blankets. Systems made up of thin metallic sheets and a network of plastic spacers are designated rigidized superinsulation.

III. Properties: Maximum continuous service temperatures for various materials commonly used in insulation systems are shown in Table B.1. Weight information is a function of particular system design and is shown on the data sheets following. No information was found on comparative costs for the systems considered. The material cost in all cases is small relative to the cost of fabricating the total

FIGURE B.1

EFFECTIVE THERMAL CONDUCTIVITY FOR VARIOUS INSULATION SYSTEMS



Reference: B5

TABLE B.1

MAXIMUM TEMPERATURE FOR INSULATION MATERIALS

Material	T max, ^{o}F
Urethane Foam	200
Fiberglas	250-300
Mylar	300
Teflon	500
Dexiglas Paper	600
Kapton	760

Reference: B7, C1

structures, and so it is not reported. For future estimating purposes, a gross cost of $2/ sq. ft. for multilayer insulation may be assumed. (Reference B.11).

Thermal performance of insulation can be characterized by either an effective conductivity or an effective emissivity. In the former case, the two outer surfaces of the structure are coupled by k_{eff} and appropriate boundary conditions are imposed on each outer surface. When the effective emissivity is used, it is applied to the guarded surface and not the insulation itself. Both k_{eff} and ϵ eff are listed on the data sheets.

In extensive testing reported in Reference B6, it was determined that the optimum packing density for multilayer insulation (with and without spacers) is about 70 layers per inch. At this point, the value of k_{eff} was a minimum. Tests were performed at below 10^{-6} torr and the temperature range was 70^{o}F to -320^{o}F.

IV. Problems/Failure: Gross failure of an insulation system can occur only by physical removal from the guarded surface. Performance can be degraded (heat leak increased) by compression, exposure to moisture, and elevated temperature, or improper handling techniques.

It has been shown (Ref. B1) that lateral conductance of a multilayer blanket is 10^3 to 10^6 times the transverse conductance. Consequently, techniques used for fastening and joining blankets must be evaluated to minimize overall system heat leak.

Attempts to predict the performance of multilayer insulation with theoretical models have been unsuccessful. Neither pure conduction or pure radiation analyses can match test data. It is apparent that empirical testing is necessary to evaluate the effectiveness of these systems.

V. Data Sheets: Properties for specific insulation systems are indicated on the following data sheets.

INSULATION

No.	Classification	Complete Description	Thickness (In.)	Effective ϵ	Effective k x 10^5 (BTU/Hr-Ft-^oF)	Test Temperature Range (^oF)	Weight $\left(\frac{\#}{CU\ FT}\right)$	Reference	Comments
1	Multilayer	35 layers ¼mil mylar, aluminized 1 side and crinkled	.50	.0022	3.2	T_H = 73 T_C=-322	1.52	B1	
2	Multilayer	35 layers ¼mil mylar, aluminized 1 side and crinkled	.50	.0035	5.0	T_H = 71 T_C = -322	1.45	B1	Same as No. 1 above; sample seemed tight in test apparatus
3	Multilayer	35 layers ¼mil mylar, aluminized 1 side and double crinkled	.50	.0027	3.9	T_H = 71 T_C =-323	1.46	B1	Did not entirely fill .50 in. test gap.
4	Multilayer	35 layers ¼mil mylar, aluminized 1 side and double crinkled	.85	.0023	5.7	T_H = 72 T_C=-323	.86	B1	
5	Multilayer	51 layers ¼ mil mylar, aluminized 2 sides, embossed	.40	.0030	3.3	T_H = 68 T_C=-322	2.79	B1	
6	Multilayer	33 layers ¼ mil mylar, aluminized 1 side and crinkled plus 2 layers ½ mil Kapton, aluminized 1 side, crinkled and installed next to cold plates	.50	.0028	4.0	T_H = 72 T_C=-323	1.54	B1	

INSULATION

No.	Classification	Complete Description	Thickness (In.)	Effective ϵ	Effective $k \times 10^5$ (BTU/Hr-Ft-^oF)	Test Temperature Range (^oF)	Weight $\left(\frac{\#}{CU\ FT}\right)$	Reference	Comments
7	Multilayer	23 layers ¼ mil mylar, aluminized 2 sides; 24 layers Dacron net spacers	.50	.0022	3.2	T_H=73 T_C=-322	5.52	B1	
8	Multilayer	23 layers ¼ mil mylar, aluminized 2 sides, 24 nylon tulle spacers, 1 layer ½ mil Kapton aluminized 1 side, and installed next to cold plates	.50	.0036	5.1	T_H=68 T_C=-323	2.44	B1	
9	Multilayer	8 layers ½ mil mylar, aluminized 1 side, deeply corrugated; 8 layers ½ mil mylar, smooth reflectors. Alternately placed (Dimplar)	.75	.0061	13.1	T_H=70 T_C=-321	1.03	B1	
10	Multilayer	8 layers ½ mil mylar, aluminized 1 side deeply corrugated; 8 layers ½ mil mylar smooth reflectors. Alternately placed (Dimplar)	.85	.0043	10.5	T_H=72 T_C=-323	.905	B1	

INSULATION

No.	Classification	Complete Description	Thickness (In.)	Effective ε	Effective k x 10^5 (BTU/Hr-Ft-°F)	Test Temperature Range (°F)	Weight $\left(\frac{\#}{CU\ FT}\right)$	Reference	Comments
11	Multilayer	35 layers ¼ mil mylar-uncoated crinkled	.50	.0609	88.0	T_H= 72 T_C=-322	1.5	B1	
12	Multilayer	35 layers ½ mil mylar, tin coated 1 side and crinkled	.50	.0052	7.3	T_H=68 T_C=-322	3.22	B1	
13	Multilayer	2 layers 1 mil Kapton dimplar separating 3 layers ½ mil crinkled Kapton All aluminized 1 side	.312	.017	57.4	T_H= 150 T_C= 73	1.16	B1	
14	Multilayer	Same as 13 above	.312	.0152	66.0	T_H=251 T_C= 72	1.16	B1	
15	Multilayer	34 layers ¼ mil mylar; gold coated 1 side; crinkled	.50	.0026	3.7	T_H= 71 T_C=-324	1.84	B1	
16	Multilayer	24 layers ¼mil mylar; gold coated 1 side; crinkled	.625	.0025	4.5	T_H= 76 T_C=-323	.98	B1	
17	Multilayer	24 layers ¼ mil mylar; gold-coated 1 side; crinkled with 9-1/8 in. dia. vent holes per sq. ft.	.625	.0025	4.5	T_H = 73 T_C =-323	.97	B1	

INSULATION

No.	Classification	Complete Description	Thickness (In.)	Effective ϵ	Effective k x 10^5 (BTU/Hr-Ft-^oF)	Test Temperature Range (^oF)	Weight $\left(\frac{\#}{CU\ FT}\right)$	Reference	Comments
18	Multilayer	24 layers ½ mil Kapton; gold coated 1 side; crinkled with 9-1/8 in. dia. vent holes per sq. ft.	.625	.0053	9.6	T_H= 72 T_C=-322	1.61	B1	
19	Multilayer	19 layers ½ mil Kapton; gold coated 1 side; crinkled with 4-1/8 in. dia. vent holes per sq. ft.	.3125	.0064	5.7	T_H= 69 T_C=-321	3.11	B1	
20	Multilayer	35 layers ¼ mil mylar, aluminized 1 side and crinkled; average unperturbed sample	.50	.0028	4.0	T_H= 73 T_C=-322	1.52	B1	
21	Multilayer	Same as sample 20, except for 1 ft. of rabbetted joint per sq. ft. of insulation area		.0032	4.7	T_H= 73 T_C=-322		B1	
22	Multilayer	Same as sample 20 except for 1 1/4 in. dia. nylon insulation support post .485 in. long per sq. ft. of insulation		.0030	4.3	T_H= 73 T_C=-322		B1	

INSULATION

No.	Classification	Complete Description	Thickness (In.)	Effective ϵ	Effective k x 10^5 (BTU/Hr-Ft-^oF)	Test Temperature Range (^oF)	Weight $\left(\frac{\#}{CU\ FT}\right)$	Reference	Comments
23	Multilayer	Same as sample 20 except for rabbeted joint and nylon insulation support post		.0034	4.9	T_H= 73 T_C=-322		B1	
24	Multilayer	24 layers ¼ mil mylar; gold coated 1 side; crinkled with 9-1/8 in. dia. holes per sq. ft.	.625	.0029	11.4	T_H= 87 T_C= -50	.97	B2	
25	Multilayer	24 layers ¼ mil mylar; gold coated 1 side; crinkled with 9-1/8 in. dia. holes per sq. ft.	.625	.0028	5.3	T_H= 77 T_C=-320	.97	B2	
26	Multilayer	20 layers ¼ mil Kapton; gold coated 1side; crinkled	.40	.0025	2.8	T_H= 67 T_C=-320	1.31	B2	
27	Multilayer	20 layers ½ mil Kapton; gold coated 1 side; crinkled	.40	.0037	8.9	T_H= 72 T_C=-50	2.81	B2	
28	Multilayer	20 layers ½ mil Kapton; gold coated 1 side; crinkled	.40	.0040	33.0	T_H= 402 T_C = 70	2.81	B2	
29	Multilayer	20 layers ½ mil Kapton; gold coated 1 side; crinkled	.40	.0040	64.0	T_H= 712 T_C= 70	2.81	B2	

INSULATION

No.	Classification	Complete Description	Thickness (In.)	Effective ϵ	Effective k x 10^5 (BTU/Hr-Ft-^oF)	Test Temperature Range (^oF)	Weight $\left(\frac{\#}{CU\ FT}\right)$	Reference	Comments
30	Multilayer	70 layers ¼ mil mylar; aluminized 1 side and crinkled	1.0		8.06	T_H=104.3 T_C=94.3		B8	
31	Multilayer	Same as 30 above	1.0		8.48	T_H=144.0 T_C=94.8		B8	
32	Multilayer	Same as 30 above	1.0		3.87	T_H=11.5 T_C=.50		B8	
33	Multilayer	Same as 30 above	1.0		18.1	T_H=216.1 T_C=199.1		B8	
34	Multilayer	22 layers ¼ mil mylar aluminized both sides with alternate layers of 30 mil Goodyear foam	1.0		12.7	T_H=80.9 T_C=71.1		B8	Before outgassing at 200°F data point
35	Multilayer	Same as 34 above	1.0		14.1	T_H=110.0 T_C=99.9		B8	"
36	Multilayer	Same as 34 above	1.0		30.8	T_H=159.3 T_C=148.8		B8	"
37	Multilayer	Same as 34 above	1.0		8.14	T_H=61.3 T_C=50.4		B8	"

INSULATION

No.	Classification	Complete Description	Thickness (In.)	Effective ϵ	Effective k x 10^5 (BTU/Hr-Ft-°F)	Test Temperature Range (°F)	Weight $\left(\frac{\#}{CU\ FT}\right)$	Reference	Comments
38	Multilayer	Same as 34 above	1.0		11.3	T_H = 78.0 T_C = 66.6		B8	Before out-gassing at 200°F data point
39	Multilayer	22 layers 1/4 mil mylar aluminized both sides; with alternate layers of 30 mil Goodyear foam	1.0		30.1	T_H =204.2 T_C=193.0		B8	After out-gassing of foam at 200°F data point
40	Multilayer	Same as 39 above	1.0		5.1	T_H =76.6 T_C=-193.8		B8	"
41	Multilayer	Same as 39 above	1.0		18.4	T_H =181.3 T_C=168.1		B8	"
42	Multilayer	Same as 39 above	1.0		9.62	T_H=138.8 T_C=126.4		B8	"
43	Multilayer	Same as 39 above	1.0		6.03	T_H = 80.1 T_C =69.8		B8	"
44	Multilayer	Same as 39 above	1.0		4.68	T_H=-41.9 T_C=-51.1		B8	"

INSULATION

No.	Classification	Complete Description	Thickness (In.)	Effective ϵ	Effective k x 10^5 (BTU/Hr-Ft-^oF)	Test Temperature Range (^oF)	Weight $\left(\frac{\#}{CU\ FT}\right)$	Reference	Comments
45	Multilayer	22 layers 1/4 mil aluminized mylar separated by flocking of fiberglas on 1/2 in. centers so that fibers stand on end, ~5 mil high (Superfloc) trade name of General Dynamics/ Convair	1.0		3.68	T_H=-45.6 T_C=-54.8		B8	
46	Multilayer	Same as 45 above	1.0		6.19	T_H=12.8 T_C= 3.1		B8	
47	Multilayer	Same as 45 above	1.0		13.0	T_H=144.5 T_C=134.3		B8	
48	Multilayer	Same as 45 above	1.0		19.8	T_H=202.4 T_C=190.2		B8	

INSULATION

No.	Classification	Complete Description	Thickness (In.)	Effective ϵ	Effective k x 10^5 (BTU/Hr-Ft-°F)	Test Temperature Range (°F)	Weight $\left(\frac{\#}{CU\ FT}\right)$	Reference	Comments
49	Rigidized Super-Insulation	5 layers of Nomax paper Hexagonal Honeycomb, 3/8 in. cell size, each separated by a layer of aluminized Kapton. The outside layers are 3 mil aluminum foil. The constituents are bonded with Narmco 3135 adhesive. Foil perforated with .01 in. holes on .30 in. centers.	.60	.0148	26.6	T_H =78.3 T_C =-320		B3	
50	Rigidized Super-Insulation	Same as 49 above	.60	.0132	45.9	T_H=99.7 T_C=-102		B3	
51	Rigidized Super-Insulation	Same as 49 above	.60	.0150	101.3	T_H=198.5 T_C= 80		B3	
52	Rigidized Super-Insulation	Same as 49 above	.60	.0141	96.5	T_H =198.1 T_C= 70		B3	

No.	Classification	Complete Description	Thickness (In.)	Effective ϵ	Effective k x 10^5 (BTU/Hr-Ft-^oF)	Test Temperature Range (^oF)	Weight $\left(\frac{\#}{CU\ FT}\right)$	Reference	Comments
53	Rigidized Super-Insulation	10 layers of Hexcel mylar perforated honeycomb; 5 mil thick cell walls .75 in. cell size each separated by a layer of aluminized mylar bonded together with Epon 815 epoxy resin catalyzed with Teta. The outside layers are 3 mil aluminum foil	.917	.0374	267.	T_H=78.0 T_C=17.8	3.74	B4	Staggered honeycomb layers
54	Rigidized Super-Insulation	Same as 53 above	.917	.0368	411.	T_H=207.0 T_C= 73.4	3.74	B4	"
55	Rigidized Super-Insulation	Same as 53 above	.917	.0413	274.	T_H=105.5 T_C=-26.8	3.74	B4	"
56	Rigidized Super-Insulation	Same as 53 above except that honeycomb layers were aligned	.904	.0388	219.	T_H=82.7 T_C=-52.5	3.70	B4	
57	Rigidized Super-Insulation	Same as 56 above	.904	.0393	223.	T_H=82.5 T_C=-49.2	3.70	B4	

No.	Classification	Complete Description	Thickness (In.)	Effective ϵ	Effective k x 10^5 (BTU/Hr-Ft-^oF)	Test Temperature Range (^oF)	Weight $\left(\frac{\#}{CU\ FT}\right)$	Reference	Comments
58	Rigidized Super-Insulation	Same as 56 above except that honeycomb layers were staggered and cell wall thickness was 3 mils.	.870	.0434	237.0	T_H=80.8 T_C=-48.6	2.21	B4	
59	Rigidized Super-Insulation	Same as 58 above	.870	.0333	339.0	T_H=180.5 T_C= 74.9	2.21	B4	
60	Rigidized Super-Insulation	5 layers of Hexcel mylar perforated honeycomb; 5 mil thick cell walls, .75 in. cell size, each separated by a layer of aluminized mylar bonded together Epon 815 catalyzed with teta. The outside layers are 3 mil aluminum foil. Staggered honeycomb layers.	.468	.0901	261.0	T_H=77.2 T_C=-49.3	5.81	B4	
61	Rigidized Super-Insulation	Same as 60 above	.468	.0845	296.	T_H=108.8 T_C=-18.3	5.88	B4	

INSULATION

No.	Classification	Complete Description	Thickness (In.)	Effective ε	Effective k x 10^5 (BTU/Hr-Ft-°F)	Test Temperature Range (°F)	Weight $\left(\frac{\#}{CU\ FT}\right)$	Reference	Comments
62	Rigidized Super-Insulation	Same as 60 above	.468	.0854	334.	T_H=130.1 T_C=-0.7	5.88	B4	
63	Rigidized Super-Insulation	Same as 60 above	.468	.0836	368.	T_H=150.3 T_C=19.9	5.88	B4	
64	Rigidized Super-Insulation	Same as 60 above	.468	.0779	419.0	T_H=189.4 T_C=58.7	5.88	B4	
65	Rigid Foam	"Isonate" foam (CPR-11-16) (Urethane)	2.0		2770.	T_H=125.4 T_C=112.9	13.0	B8	
66	Rigid Foam	Same as 65 above	2.0		3020.	T_H=212.4 T_C=207.7	13.0	B8	
67	Rigid Foam	Same as 65 above	2.0		2590.	T_H=-14.1 T_C=-22.4	13.0	B8	
68	Rigid Foam	Same as 65 above	2.0		2670.	T_H=30.3 T_C=23.5	13.0	B8	
69	Rigid Foam	Same as 65 above	2.0		2680.	T_H=81.9 T_C=73.0	13.0	B8	

C. Space Radiators

I. Purpose: Radiators are employed to provide strong radiative coupling between heat sources and deep space. They are sized to reject internal heat loads while maintaining acceptable temperatures in critical components.

II. Types: There are two major types of radiators; passive and active. A passive radiator is simply a piece of structure which is exposed to space and is conductively and/or radiatively coupled to internal heat sources. Virtually all unmanned spacecraft flown to date have employed passive radiators. Active radiators have integral coolant lines or heat pipes to improve the effective source/sink coupling. The BIOS satellite, Apollo Command Module, and Apollo Instrument Unit have utilized liquid coolant loops with associated active radiators. No spacecraft to date has used heat pipe radiators, although ATS-E incorporated heat pipes into solar panel substrates to overall panel gradients.

Because it is impossible to list properties of all radiators flown, data has been compiled for commonly used radiator materials only.

III. Properties: Cost and weight information for radiator metals is shown on the data sheets of this section. Maximum service temperature is determined by structural limits only and depends on application.

IV. Problems/Failure: Passive radiators are extremely reliable. Degradation in performance is due to increase of solar absorptivity of the applied coating (see Section A) and not the radiator itself. The major problem associated with passive radiators is maintaining a high radiation efficiency over the element surface.

Failure of active radiators will occur if the coolant lines or heat pipes are punctured causing loss of fluid. Adequate quality control can prevent fluid loss at welds and shielding or redundant tubes can decrease the probability of failure due to puncture by meteoroid impact to acceptable levels.

V. Data Sheets: Following are data sheets for metals commonly considered or used for space radiators. Where a property is dependent on specific temper, the temper is given in parenthesis before the quoted value.

SPACE RADIATORS

No.	Metal	Composition	Temperature (^{o}F)	Conductivity (BTU/Hr-Ft-^{o}F)	Density $\left(\frac{\#}{CF}\right)$	Heat Capacity $\left(\frac{BTU}{\#}\right)$	Bare Emissivity	Yield Strength (KSI)	Cost $\left(\frac{\$}{\#}\right)$	Reference	Comments
1	Aluminum	1100 AL 99% min.	77	128	169	.22		(0) 5 (H14)17 (H18)22	.443 to .473	C1	
2	Aluminum	6061	77	(0)99.2 (T4)89.5 (T6)89.5	169	.23	.035-.08	(0) 8 (T4)21 (T6)40	.477 to .540	C1, C2, C3	
3	Aluminum	2024	77	(0)108.9 (T3)70.2 (T4)70.2 (T6)87.1	172.8	.22	.035-.08	(0)11 (T3)50 (T4)47 (T6)57	~.50	C1, C2, C3	
4	Aluminum	7075	77	(0)99.2 (T6)72.6	174.5	.23	.035-.08	(0)15 (T6)73	~.50	C1, C2,C3	
5	Magnesium	AZ31B	68	(H24) 44	110.6	.245	.12 (pol-ished)	(H24) 24-27	.702 to 1.98	C1, C2	
6	Stainless Steel	301	212	9.4	501.1	.12	.09	140 for sheet-cold worked	.388 to .643	C1	
7	Stainless Steel	304	212	9.4	501.1	.12	.09	75 for bar cold worked	.388 to .643	C1	
8	Stainless Steel	321	212	9.4	501.1	.12	.09	30 for plate anneal	.500 to .833	C1	
9	Beryllium	Com-merci-ally pure	212	87	115.8	.45		5-20 anneal, depends on form	250.00 to 750.0	C1	

SPACE RADIATORS

No.	Metal	Composition	Temperature (^oF)	Conductivity (BTU/Hr-Ft-^oF)	Density $\left(\frac{\#}{CF}\right)$	Heat Capacity $\left(\frac{BTU}{\#}\right)$	Bare Emissivity	Yield Strength (KSI)	Cost $\left(\frac{\$}{\#}\right)$	Reference	Comments
10	Titanium	6AL-4V	68	4.2	276.5	.135	.08	128, 155 at room temp.; 78,100 (aged) at 800°	9.40	C1	
11	Copper	102 Oxygen free copper	68	226	558	.092		10-11 anneal, 40-50 hard	.823 to .938	C1	

D. Louvers

I. Purpose: Thermal control louvers (or shutters) are used to vary the effective radiative properties of a baseplate radiator as a function of local temperature. This is accomplished by regulating the position of radiation barriers relative to the baseplate.

II. Types: Louvers can be classified by configuration, blade description, and actuator type. Two basic configurations have been flown: 1) a series of small blades which rotate to an open position normal to the baseplate, and 2) a cruciform structure which rotates within a plane to expose a high emissivity section of the baseplate. Blades have ranged from a thin (10 mil) sheet of polished aluminum to hollow structures of formed aluminum foil to frames covered with multilayer insulation.

Bimetallic and fluid actuation systems have been developed and flown to provide temperature-sensitive control of blade position. The former system relies on the differential expansion of a bimetallic spring to rotate either one or two blades as a function of spring temperature. The spring and baseplate are thermally coupled by radiation only. Fluid systems use either bulk liquid thermal expansion or increase in saturation pressure with temperature within a closed volume bellows or piston to provide actuation force. A mechanical linkage connects the bellows to all blades of the system. Coupling between the baseplate and sensor device is conductive.

III. Properties: The performance of a louver system is usually expressed in terms of effective radiation properties. Thus the effective emissivity of a system is the emissivity value which, when applied to the baseplate alone (no louvers), yields the same thermal balance as that attained with the louvers. Effective absorptivity is treated in the same manner.

Empirical testing may be used to generate curves of effective emissivity versus temperature for a louver system. A perfect system would have an ϵ eff of zero in the closed position and an ϵeff equal to the baseplate coating emissivity in the fully open position. Real systems have some small heat leak when closed and cannot attain the baseplate emissivity when open because of interaction with the relatively warm blades. The range of effective emissivities reported for the various systems flown is shown on the data sheets of this section. System weights are also given.

The operational temperature range of a louver system can be controlled by material selection and assembly techniques used in the actuator.

IV. Problems/Failure: Failure of an entire louver system will occur when all of the blades fail to respond to temperature changes within the control range. This condition is more likely in gang-actuated systems than in systems with individual blade actuation. A bearing failure for one blade of the ganged system will prevent movement of other blades and cause system failure. The single blade failure will generally cause only slightly degraded performance in an individual activation system.

Credible failure points in a louver assembly are: 1) actuator (bellows or bimetallic element), 2) louver springs, 3) linkage bearings or fatigue points, 4) blade shaft bearings or flex pivots. Failure rate data for these elements is shown in Table D.1.

Assessment of the overall system reliability involves manipulation of four quantities: 1) failure rates, 2) operational time, 3) number of units per system, and 4) number of allowable failures per system. Since items 2, 3 and 4 depend on specific design and analysis, reliability figures are not presented here. Suffice it to say that total reliability figures of .99 or better can be obtained (on paper) for either type of actuation system.

TABLE D1

FAILURE RATES FOR LOUVER SYSTEM COMPONENTS

Component	Failures/10^6 hours
Bellows	.09
Bimetallic elements	.01
Louver springs	.05
Bearings	.02
Flex pivots	.02

Reference: GE In-house studies

Analytical evaluation of louver performance is complicated by reflection and re-radiation of energy between the blades and the baseplate. References D6, D11, and D12 present such theoretical studies. The effect of external panels on system performance is discussed in References D2 and D5.

V. Data Sheets: The following data was compiled for several louver systems flown. Estimated cost data was available for the NIMBUS system only.

LOUVERS

Actuator Type	Blade Description	Functional Temperature Range (°F)	Emissivity Range	Absorptivity Range	Cost $/(SF)	Flown On	Weight #/(SF)	Design Life (Yrs)	Unit Size (SF)	Performance	Reference	Comments
Bellows	Al. form wrapped with 15 layers of al. mylar	66-81	.15-.65		3700	Nimbus	3.1	.5	.8	Good	D3	Fluid (Freon-114) actuated. No failures in 64 systems flown to date.
Bi-metallic	Polished alum.	Typically 75-95	.08-.61			OAO Pegasus Nimbus	1.5	1.0	2.17 2.22	Satisfactory	D1	Internal systems (radiate to vehicle skin)
Bi-metallic	20 mil polished alum.	(None given)	.08-.72			Mariner II	1.76		1.25	Satisfactory	D2	
Bi-metallic	10 mil polished alum.	55-80	.12-.76			Mariner C	0.8		1.62		D2	
Bi-metallic	Rect. cross-section of 3 mil al. foil	40-85	.20-.73			Pioneer			~4		D4	Annular system. ϵ range can be improved to .07-.82

E. Phase Change Materials

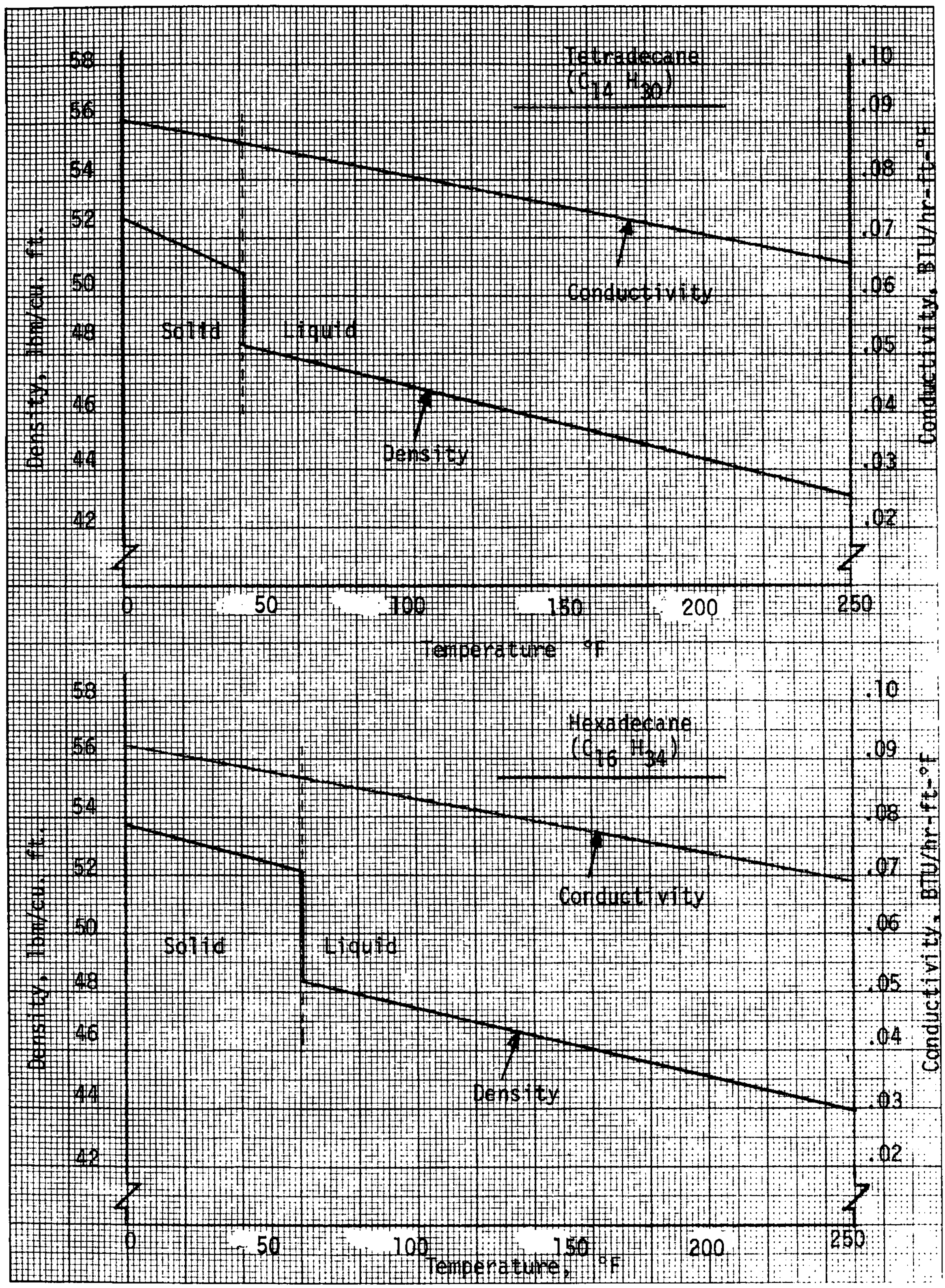
I. Purpose: The purpose of a device containing a phase change material (PCM) is to absorb heat isothermally when the temperature of its surroundings is increased and to reject the heat isothermally when the surroundings cool. In this way, the device tends to damp out temperature excursions of its environment.

II. Types: A distinction must be made between the PCM itself and the thermal control device containing the PCM. A list of the desirable properties of the PCM can be compiled (see Ref. E5) and used to evaluate candidate materials. The configuration of the overall device, however, is much more difficult to define. Testing to date has revealed many design problems (discussed below) that have not been adequately solved. Thus, this thermal control technique remains in the development phase.

Information on several candidate PCM's has been accumulated and is shown on the data sheets. No data is included on containment devices because no system is currently regarded as fully acceptable for spacecraft thermal control.

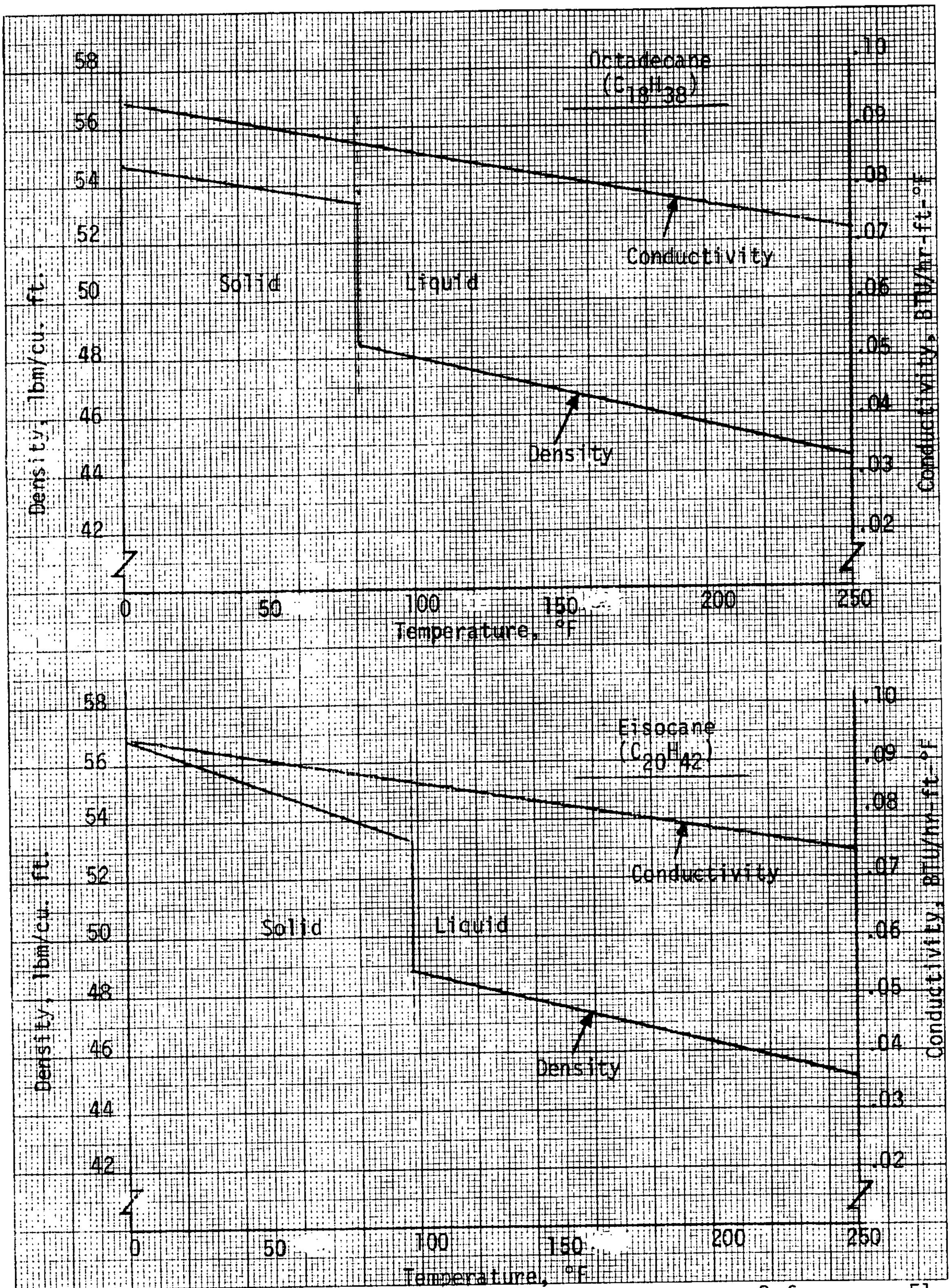
III. Properties: The important physical properties of a PCM are high density, melting point, high heat of fusion and high conductivity (both solid and liquid). In addition, the solid-liquid transition must be reversible at a repeatable temperature. The PCM should be chemically stable and non-reacting with the containment vessel.

The normal paraffins are probably the most likely PCM candidates for systems operating at normal housekeeping temperatures. Figures E.1 and E.2 show solid and liquid density and thermal conductivity for four n-paraffins as a function of temperature. Other properties can be found on the following data sheets.



Reference: E1

FIGURE E.1



Reference: E1

FIGURE E.2

IV. Problems/Failure: The only obvious failure made for a PCM device is loss of PCM. Until a satisfactory containment scheme is defined, no reliability assessment can be made.

The problems encountered during design, development and test of PCM devices are discussed below.

1) The PCM must be kept in good thermal contact with the heated/cooled surface at all times. Furthermore, performance can be seriously degraded if liquid is allowed to accumulate near the heated surface and introduce a large thermal resistance between the surface and the unmelted PCM. The same is true for the solid during the cooling cycle.

2) The volumetric expansion and contraction of the PCM in both phases must be considered.

3) Supercooling of the liquid below its normal melting point has been observed in some systems. The addition of a catalyst to provide nucleation sites seems to aid somewhat but does not fully relieve the problem.

4) The purity of the PCM can significantly effect its performance.

5) Convection currents in 1-g testing can disguise potential problems in space.

V. Data Sheets: Data sheets follow which list PCM properties.

Reference E6 presents a very good compilation of properties of many considered PCM's. In addition, it describes computational techniques & computer codes necessary to estimate PCM system characteristics for specific applications.

PHASE CHANGE MATERIAL

Name	Symbol	Melting Temperature (°F)	Heat of Fusion ($\frac{BTU}{\#}$)	Density ($\frac{\#}{CF}$)	Liquid Conductivity (BTU/Hr-Ft-°F)	Solid Conductivity (BTU/Hr-Ft-°F)	Cost ($\frac{\$}{\#}$)	Flown On	Configuration Description	Reference	Comments
Tetradecane	$C_{14}H_{30}$	41	98	See	curves		13,00			E1	
Hexadecane	$C_{16}H_{34}$	61	102	See	curves		13,00			E1	
Octadecane	$C_{18}H_{38}$	81	105	See	curves		13,00			E1	
Eicosane	$C_{20}H_{42}$	98	106	See	curves		80,00			E1	
Lithium Nitrate Trihydrate with Zinc Hydroxy nitrate catalyst	$LiNo_3 \cdot 3H_2O$	86	128							E2	
Acetamide	CH_3CONH_2	178	104							E2	
Methyl Fumarate	$(CHCO_2CH_3)_2$	216	104							E2	
Myristic Acid	$CH_3(CH_2)_{12}COOH$	136	86							E2	
Polyethylene Glycol (Carlowax 600)		68-77	63	70 @ 68°F	.0924 @ 122°F .0922 @ 194°F					E3	

PHASE CHANGE MATERIAL

Name	Symbol	Melting Temperature (^{o}F)	Heat of Fusion ($\frac{BTU}{\#}$)	Density ($\frac{\#}{CF}$)	Liquid Conductivity (BTU/Hr-Ft-^{o}F)	Solid Conductivity (BTU/Hr-Ft-^{o}F)	Cost ($\frac{\$}{\#}$)	Flown On	Configuration Description	Reference	Comments
Dibasic Sodium Phosphate	$Na_2HPO_4 12H_2O$	97	122	94.8			5.0			E4	
Dihydrode-carborane	$B_{10}H_{14}$	211	113	93.						E4	
Aluminum Chloride	$ALCl_3$	378	115	152						E4	
Sodium Hydroxide	N_aOH	605	90	133			1.0			E4	
Transit Heet 60		60	100							E5	
Transit Heet 86		86	130							E5	
Nitrogen Pentoxide	N_2O_5	86	138	102.5						E5	
Sodium Sulfate	$Na_2SO_4 10H_2O$	88	92	91						E5	
Glycerol	$C_3H_5(OH)_3$	64.4	85							E5	

F. Interfaces

The thermal contact resistance between two adjoining surfaces is often a significant factor in the calculation of total temperature drop along a heat flow path. The magnitude of this resistance is dependent upon contacting metals, pressure, surface finishes and interstitial medium. No analytical model has demonstrated sufficient accuracy in predicting contact phenomena for design purposes, and conservative values based on empirical tests are usually assumed.

The data sheets that follow present interface information in the form of apparent h's (contact conductance in BTU/hr-sq. ft-°F) for various metals, finishes and contact pressures. Some data is given for interstitial materials used to improve the effective contact conductance.

Reference F7 presents a compilation of empirical interface data and a set of guidelines for estimation of contact conductance based on this data.

METAL TO METAL INTERFACES

Filler Material	Metal, Thickness (In)	Metal, Thickness (In)	Surface Finish	Contact Pressure (PSI) $\times 10^{-3}$	Bolt Spacing (In)	Bolt Torque (in - #)	Ambient Pressure	Apparent h (BTU/Hr-SF-°F) $\times 10^{-3}$	Filler Cost ($\frac{\$}{\#}$)	Filler Density ($\frac{\#}{CF}$)	Reference	Filler Flown On	Comments
None	2 Al 7075-T6 cylinders (1" diameter)		Opt.	.12 .28 .44 .52 .59			10^{-5} torr	.79 1.55 2.44 2.60 3.09			F2		
MSD 104 Grease Type I (5% Ag)	(same as above)			.16 .28 .38 .51 .55			same	5.75 8.40 7.90 12.5 12.0			F2		
MSD 104 Grease Type II (60% Ag)	(same as above)			.32 .45 .60			same	6.0 5.8 10.2			F2		
Ecco-therm TC-4	(same as above)			.43 .57 .63 .79			same	5.5 7.6 9.0 16.5			F2		
None	2 SS 304 cylinders (1" diameter)		Milled	.23 1.81 4.20			10^{-5} torr	.07 .23 1.24			F1		RMS finishes= 300 μin.
None	2 Al 7075-T6 cylinders (1" diameter)		Milled	.56 1.81 3.02			same	1.50 6.76 8.64			F1		RMS finishes= 160 μin.
None	2 Ti 6AL4V cylinders (1" diameter)		Opt.	.83 2.02 2.68			same	.13 .52 2.16			F1		RMS finishes= 4 μin.

C-2

METAL TO METAL INTERFACES

Filler Material	Metal, Thickness (In)	Metal, Thickness (In)	Surface Finish	Contact Pressure (PSI)x10^{-3}	Bolt Spacing (In)	Bolt Torque (in - #)	Ambient Pressure	Apparent h (BTU/Hr-SF-°F) x10^{-3}	Filler Cost ($\frac{\$}{\#}$)	Filler Density ($\frac{\#}{CF}$)	Reference	Filler Flown On	Comments
None	2 Mag AZ31B cylinders (1" diameter)		Opt.	.47 1.51 2.67			10^{-5} torr	.96 4.97 21.3			F1		RMS finishes= 4 μin.
None	2 Al 7075-T6 (1" diameter)		Opt.	.53 1.31 2.48			same	1.24 4.78 23.7			F1		RMS finishes= 4 μin.
None	2 Ti 6AL4V cylinders (1" diameter)		Milled	.15 .75 2.80			same	.12 .53 7.36			F1		RMS finishes= 200 μin.
None	2 Al 7075-T6 cylinders (1" diameter)		Milled	.34 1.08 3.44			same	24.0 27.7 46.3			F1		RMS finishes= 250 μin.
None	2 Cu OFHC cylinders (1" diameter)		Opt.	.03 .33 1.11			same	1.31 1.78 2.49			Fi		RMS finishes= 4 μin.

METAL TO METAL INTERFACES

Filler Material	Metal, Thickness (In)	Metal, Thickness (In)	Surface Finish	Contact Pressure (PSI)	Bolt Spacing (In)	Bolt Torque (in - #)	Ambient Pressure	Apparent h_o (BTU/Hr-SF-°F) $\times 10^{-3}$	Filler Cost ($\frac{\$}{\#}$)	Filler Density ($\frac{\#}{CF}$)	Reference	Filler Flown On	Comments
None	7075-T6 Al-.11	7075-T6 Al-.16	63 μin. RMS		1.5 2.0 2.5	75 75 75	10^{-4} torr	.34 .23 .21			F3		1" overlap joint
None	(same as above)		125 μin. RMS		1.5 2.0 2.5	75 75 75	same	.43 .25 .17			F3		Same as above
None	7075-T6 Al-.45	7075-T6 Al-.46	63 μin. RMS		2.0 2.0 2.0	50 75 100	same	.96 1.39 1.48			F3		Same as above
None	(same as above)		125 μin. RMS		2.0 2.0 2.0	50 75 100	same	.78 1.07 1.19			F3		Same as above

G. Heat Pipe Fluids

The following data sheets list the important physical and thermal properties for various heat pipe fluids. These properties are shown graphically for five fluids applicable in the housekeeping temperature range following the data sheets.

FLUID WATER

Chemical Symbol H_2O

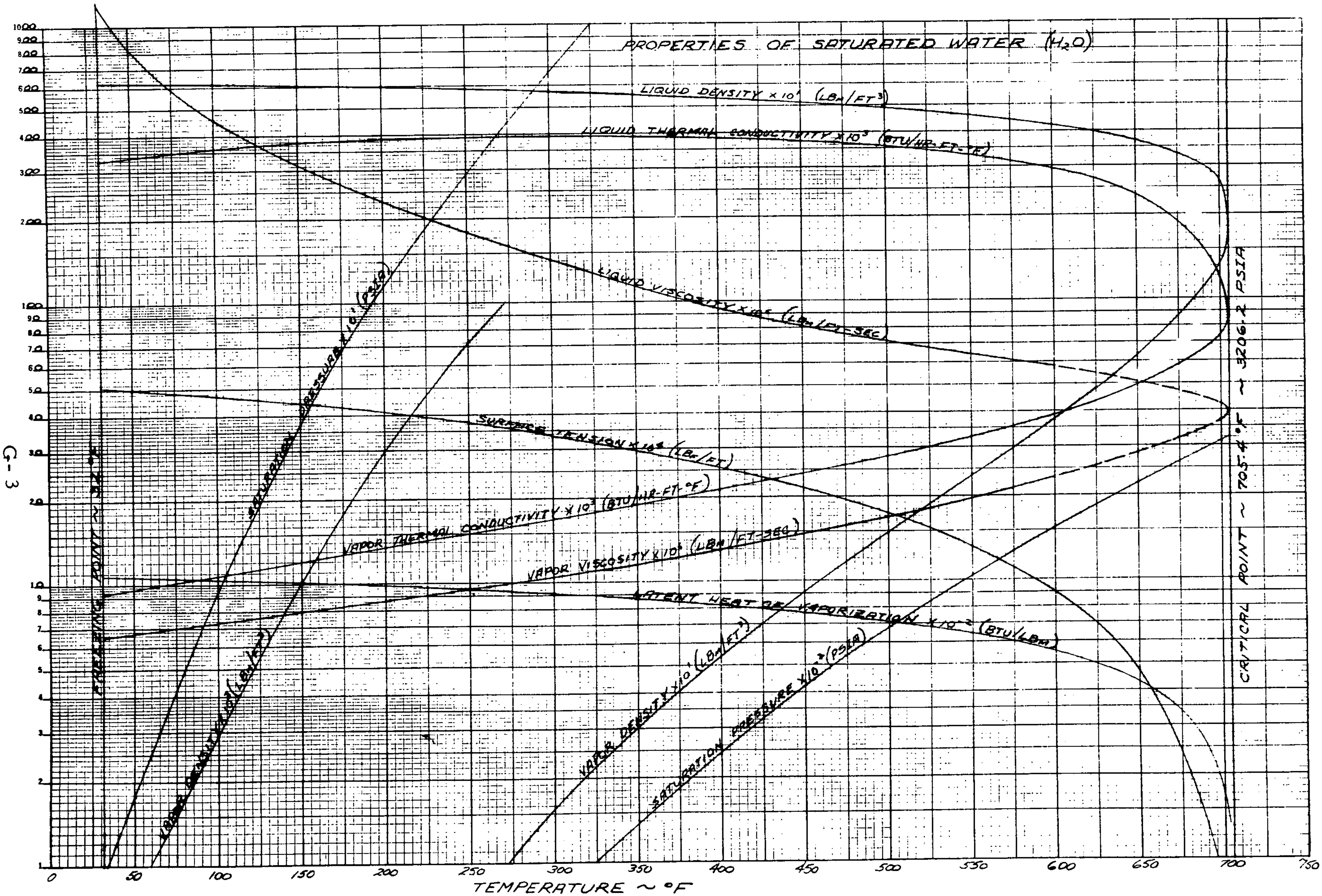
Molecular Weight 18.016

Freezing Point (°F) 32.0

Critical Temperature (°F) 705.4

Critical Pressure (psi a) 3206.2

TEMP	Psat	Hfg	DENSITY				VISCOSITY				CONDUCTIVITY				SURF. TEN.		FOM
			Liquid		Vapor		Liquid		Vapor		Liquid		Vapor				
°F	psi a	B/lbm		lbm/ft³		lbm/ft³	T, °F	lbm/ft-sec x10⁵	T, °F	lbm/ft-sec x10⁵	T, °F	B/h-ft-°F	T, °F	B/h-ft-°F	T, °F	lbf/ft x10⁴	
32.0	.0885	1075.8		62.42		.0003		120.6		.6435	32.0	.326	32.0	.009			
50.0	.1781	1065.6		62.38		.0006					68.0	.346			50.0	50.8	
100.0	.9492	1037.2		62.00		.0029		45.8			104.0	.363			104.0	47.7	
150.0	3.718	1008.2		61.20		.0103					140.0	.377			150.0	44.7	
200.0	11.526	977.9		60.13		.0297		20.59		.8687	212.0	.387	200.0	.013	200.0	41.2	
250.0	28.82	945.5		58.82		.0724									250.0	37.4	
300.0	67.01	910.1		57.31		.1547						.395			300.0	33.3	
350.0	134.6	870.7		55.59		.2992											
400.0	247.3	826.0		53.65		.5367		9.33		1.287	420.0	.376	400.0	.021			
450.0	422.6	774.5		51.55		.9097											
500.0	680.8	713.9		49.02		1.482					520.0	.340					
550.0	1045.2	640.8		45.87		2.358											
600.0	1542.9	548.5		42.37		3.748		5.79		2.317	620.0	.275	600.0	.038			
650.0	2208.2	422.8		37.31		6.188											
700.0	3093.7	172.1		27.10		13.14											
705.4	3206.2	0.0		19.88		19.88										0.0	
REFER	G1	G1		G1		G1		G1		G1		G2		G1		G3	


PROPERTIES OF SATURATED WATER (H_2O)
LIQUID DENSITY × 10' (LBM/FT³)
LIQUID THERMAL CONDUCTIVITY × 10³ (BTU/HR-FT-°F)
LIQUID VISCOSITY × 10⁵ (LBM/FT-SEC)
SATURATION PRESSURE × 10' (PSIA)
SURFACE TENSION × 10⁴ (LBF/FT)
VAPOR THERMAL CONDUCTIVITY × 10³ (BTU/HR-FT-°F)
VAPOR VISCOSITY × 10⁵ (LBM/FT-SEC)
LATENT HEAT OF VAPORIZATION × 10⁻² (BTU/LBM)
VAPOR DENSITY × 10' (LBM/FT³)
SATURATION PRESSURE × 10⁻³ (PSIA)
FREEZING POINT ~ 32°F
CRITICAL POINT ~ 705.4°F ~ 3206.2 PSIA
TEMPERATURE ~ °F
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750
1 2 3 4 5 6 7 8 9 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 20.0 30.0 40.0 50.0 60.0 70.0 80.0 90.0 100.0

FLUID AMMONIA

Chemical Symbol NH_3

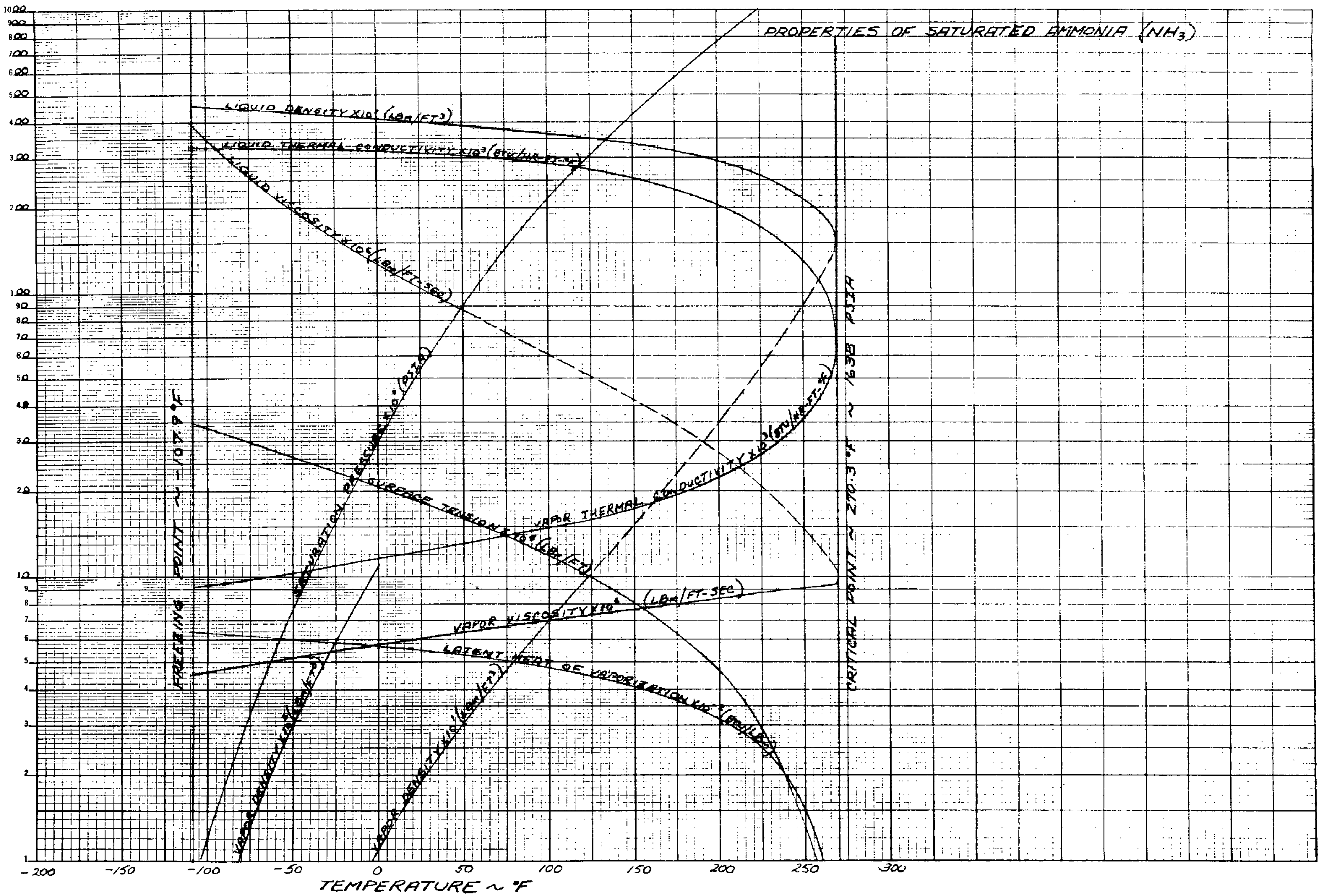
Molecular Weight 17.03

Freezing Point (°F) -107.9

Critical Temperature (°F) 270.3

Critical Pressure (psia) 1638

TEMP	P_{sat}	Hfg	DENSITY				VISCOSITY				CONDUCTIVITY				SURF. TEN.		FOM
			Liquid		Vapor		Liquid		Vapor		Liquid		Vapor				
°F	psia	$\frac{B}{lb_m}$		$\frac{lb_m}{ft^3}$		$\frac{lb_m}{ft^3}$	T, °F	$\frac{lb_m \times 10^2}{ft\text{-}sec}$	T, °F	$\frac{lb_m \times 10^6}{ft\text{-}sec}$	T, °F	$\frac{B}{h\text{-}ft\text{-}°F}$	T, °F	$\frac{B}{h\text{-}ft\text{-}°F}$	T, °F	$\times 10^4$ $\frac{lb_f}{ft}$	
-107.9									-107.9	4.516							
-94.0				45.30		.0070	-92.2	.0319									
-50.0	7.67	604.3		43.49		.0302	-58.0	.0213									
							-40.0	.0185			-20.0	.317	-40.0	.0105	-20.0	28.10	
0.0	30.42	568.9		41.34		.1097			32.0	6.169	0.0	.316	0.0	.0117			
							20.0	.0108			32.0	.312	20.0	.0123			
50.0	89.19	527.3		39.00		.3036	40.0	.0094			50.0	.307	40.0	.0129	52.0	15.76	
							60.0	.0081	68.0	6.599	80.0	.293	80.0	.0142			
100.0	211.9	477.8		36.40		.7048							100.0	.0149	93.4	12.40	
124.0	303.4	450.1		35.00		1.01			122.0	7.338	120.0	.275	120.0	.0156			
150.0				33.60											138.2	8.908	
200.0				29.50													
270.3	1638	0.0		16.0		16.0		9.401		9.401						0.0	
REFER	G2	G2		G2,G3		G2,G3		G2,G3		G2		G4		G5		G2,G6	



PROPERTIES OF SATURATED AMMONIA (NH_3)
LIQUID DENSITY X10' (LBM/FT³)
LIQUID THERMAL CONDUCTIVITY X10³ (BTU/HR-FT-°F)
LIQUID VISCOSITY X10⁶ (LBM/FT-SEC)
SATURATION PRESSURE X10⁻¹ (PSIA)
SURFACE TENSION X10⁴ (LBM/FT)
VAPOR THERMAL CONDUCTIVITY X10³ (BTU/HR-FT-°F)
VAPOR VISCOSITY X10⁶ (LBM/FT-SEC)
LATENT HEAT OF VAPORIZATION X10⁻² (BTU/LBM)
VAPOR DENSITY X10² (LBM/FT³)
VAPOR DENSITY X10 (LBM/FT³)
FREEZING POINT ~ -107.9°F
CRITICAL POINT ~ 270.3°F ~ 1638 PSIA
TEMPERATURE ~ °F

FLUID METHANOL

Chemical Symbol CH_3OH

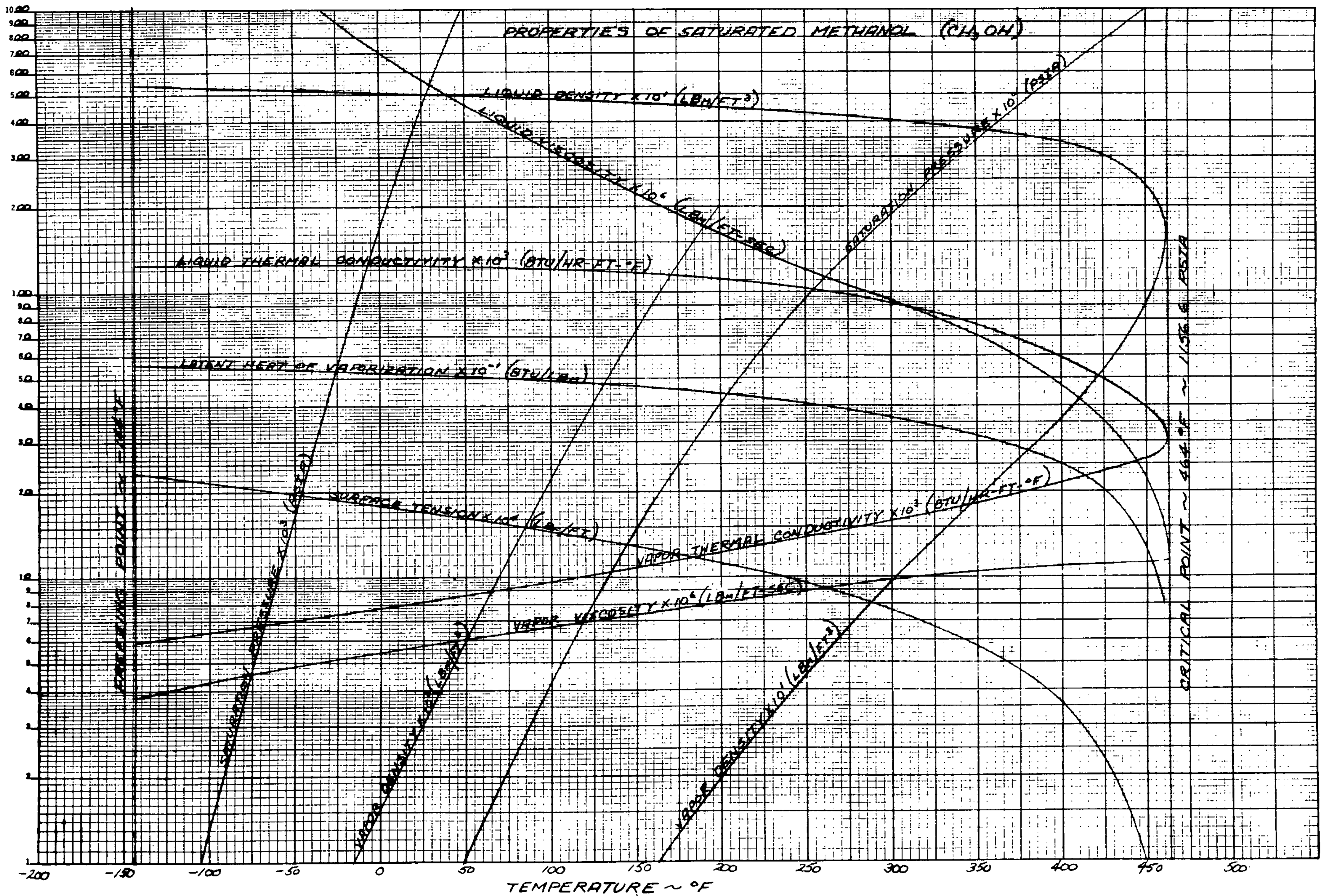
Molecular Weight 32.04

Freezing Point (^oF) -144

Critical Temperature (^oF) 464.0

Critical Pressure (psi a) 1156.6

TEMP	P_{sat}	Hfg	DENSITY				VISCOSITY				CONDUCTIVITY				SURF. TEN.		FOM
			Liquid		Vapor		Liquid		Vapor		Liquid		Vapor				
^oF	psi a	$\frac{B}{lb_m}$		$\frac{lb_m}{ft^3}$		$\frac{lb_m}{ft^3}$	T, ^oF	$\frac{lb_m}{ft\text{-}sec}$ x10^2	T, ^oF	$\frac{lb_m}{ft\text{-}sec}$ x10^6	T, ^oF	$\frac{B}{h\text{-}ft\text{-}^oF}$	T, ^oF	$\frac{B}{h\text{-}ft\text{-}^oF}$	T, ^oF	x10^4 $\frac{lb_f}{ft}$	
									-144.0	3.80							
-47.2	.019								-100.0	4.30							
2.8	.193						-20.0	.086	-50.0	4.85							
41.0	.772						0.0	.071	0.0	5.45	30.0	.123	32.0	.0083			
50.0	1.05	507.0		49.9		.006.		.046		6.05	50.0	.122			50.0	16.2	
											100.0	.120					
150.0	15.1	472.0		46.7		.074		.022		7.39	150.0	.118			150.0	12.9	
200.0	40.3	443.0		45.0		.200		.016			180.0	.117	212.0	.0128	200.0	11.2	
250.0	94.7	407.0		43.0		.450		.012								9.46	
300.0	189.0	364.0		40.6		.960		.0094		9.74						7.61	
392.0	574.1			34.5		3.17			400.0	10.9							
464.0	1156.6	0.0		17.0		17.0		.0011		11.4						0.0	
REFER	G2,G3	G3		G3,G6		G3,G6		G3		G3,G9		G9		G9		G3	


PROPERTIES OF SATURATED METHANOL (CH3OH)
LIQUID DENSITY x10¹ (LBM/FT³)
LIQUID VISCOSITY x10⁶ (LBM/FT-SEC)
SATURATION PRESSURE x10⁰ (PSIA)
LIQUID THERMAL CONDUCTIVITY x10³ (BTU/HR-FT-°F)
LATENT HEAT OF VAPORIZATION x10⁻¹ (BTU/LBM)
SURFACE TENSION x10⁴ (LBF/FT)
VAPOR THERMAL CONDUCTIVITY x10³ (BTU/HR-FT-°F)
VAPOR VISCOSITY x10⁶ (LBM/FT-SEC)
SATURATION PRESSURE x10³ (PSIA)
VAPOR DENSITY
VAPOR DENSITY x10¹ (LBM/FT³)
FREEZING POINT ~ -144°F
CRITICAL POINT ~ 464°F ~ 1156.6 PSIA
TEMPERATURE ~ °F
-200 -150 -100 -50 0 50 100 150 200 250 300 350 400 450 500

FLUID FREON -11 (R-11)

Chemical Symbol CCl_3F

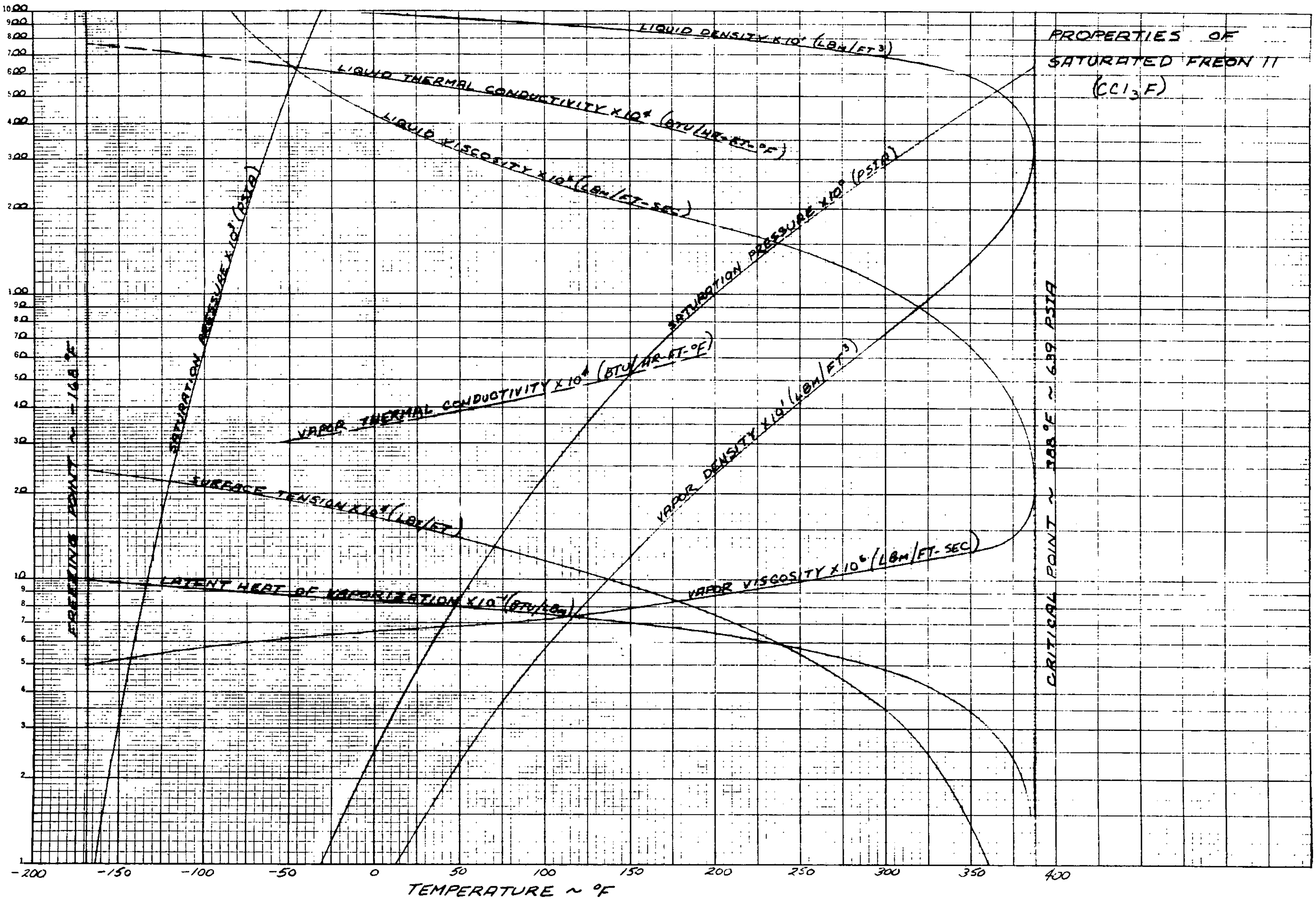
Molecular Weight 137.38

Freezing Point (°F) -168.0

Critical Temperature (°F) 388.4

Critical Pressure (psia) 639.0

TEMP	P_{sat}	Hfg	DENSITY				VISCOSITY				CONDUCTIVITY				SURF. TEN.		FOM
			Liquid		Vapor		Liquid		Vapor		Liquid		Vapor				
°F	psia	B/lbm		lbm/ft³		lbm/ft³	T, °F	lbm/ft-sec x10²	T, °F	lbm/ft-sec x10⁶	T, °F	B/h-ft-°F	T, °F	B/h-ft-°F	T, °F	lbf/ft x10⁴	
-168.0	.0008	99.2		110.4		.00004											
-150.0	.0033	97.3		109.2		.00014											
-100.0	.0624	92.4		105.6		.0022											
-50.0	.522	88.0		102.0		.0164	-40.0	.0585			-40.0	.063			-40.0	18.64	
0.0	2.56	83.9		98.3		.0721	0.0	.0434	20.0	6.65	0.0	.059	20.0	.0036	0.0	16.44	
50.0	8.78	79.7		94.3		.2270	40.0	.0343	40.0	6.72	40.0	.054	40.0	.0038	40.0	14.39	
100.0	23.5	75.2		90.2		.5670	120.0	.0234	60.0	7.12	120.0	.045	60.0	.0040	120.0	10.48	
150.0	52.4	70.4		85.8		1.21			120.0	7.39			100.0	.0045			
200.0	102.5	64.8		80.9		2.32			150.0	8.06							
250.0	182.0	58.1		75.4		4.15											
300.0	300.2	49.2		68.7		7.21											
350.0	468.1	35.5		59.3		13.00											
388.4	639.4	0.0		34.6		34.6										0.0	
REFER	G13	G13		G13		G13		G13		G3		G13		G5		G13	


PROPERTIES OF
SATURATED FREON 11
(CCl3F)
LIQUID DENSITY x 10' (LBM/FT3)
LIQUID THERMAL CONDUCTIVITY x 10⁴ (BTU/HR-FT-°F)
LIQUID VISCOSITY x 10⁴ (LBM/FT-SEC)
SATURATION PRESSURE x 10° (PSIA)
SATURATION PRESSURE x 10' (PSIA)
VAPOR THERMAL CONDUCTIVITY x 10⁴ (BTU/HR-FT-°F)
VAPOR DENSITY x 10' (LBM/FT3)
SURFACE TENSION x 10⁴ (LBF/FT)
VAPOR VISCOSITY x 10⁶ (LBM/FT-SEC)
LATENT HEAT OF VAPORIZATION x 10⁻¹ (BTU/LBM)
FREEZING POINT ~ -168 °F
CRITICAL POINT ~ 388 °F ~ 639 PSIA
TEMPERATURE ~ °F
-200
-150
-100
-50
0
50
100
150
200
250
300
350
400

FLUID FREON -113 (R-113)

Chemical Symbol $CCl_2F - CClF_2$

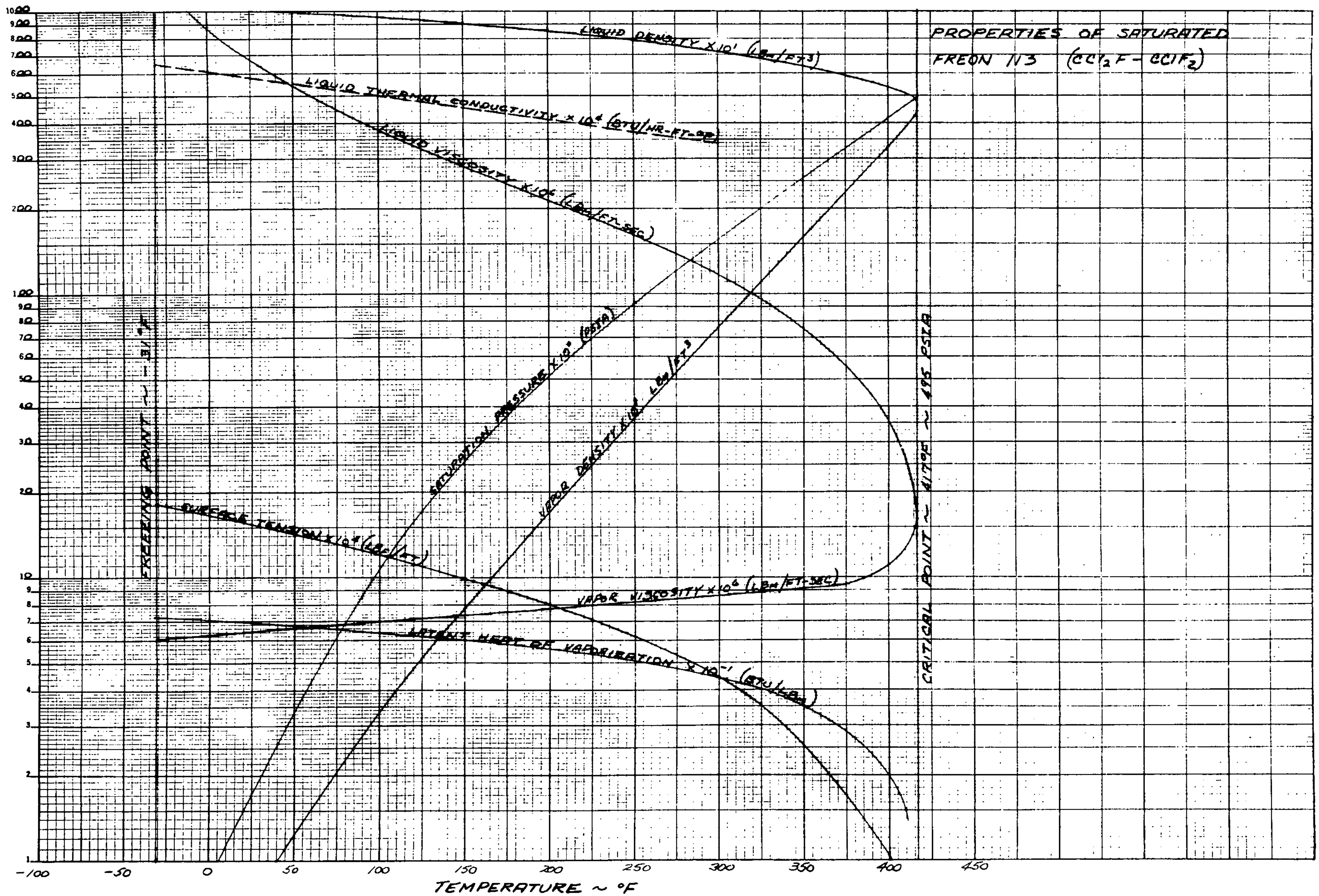
Molecular Weight 187.39

Freezing Point (°F) -31.0

Critical Temperature (°F) 417.0

Critical Pressure (psia) 495.0

TEMP	P_{sat}	Hfg	DENSITY				VISCOSITY				CONDUCTIVITY				SURF. TEN.		FOM
			Liquid		Vapor		Liquid		Vapor		Liquid		Vapor				
°F	psia	$\frac{B}{lb_m}$		$\frac{lb_m}{ft^3}$		$\frac{lb_m}{ft^3}$		$\frac{lb_m \times 10^2}{ft\text{-}sec}$		$\frac{lb_m \times 10^6}{ft\text{-}sec}$	T, °F	$\frac{B}{h\text{-}ft\text{-}°F}$		$\frac{B}{h\text{-}ft\text{-}°F}$	T, °F	$\frac{lb_f}{ft} \times 10^4$	
20.0	1.5	69.7		102		.056		.070		6.38	32.0	.0576			20.0	15.69	
40.0	2.6	68.0		100		.100		.059		6.59					40.0	14.73	
60.0	4.3	67.0		99		.140		.050		6.72					60.0	13.84	
120.0	15.5	62.0		93		.48		.033		7.06					120.0	11.17	
150.0	25.9	60.4		91		.78		.028		7.39	167.0	.0440			150.0	9.80	
REFER	G3	G3		G3		G3		G3		G3		G5				G3	


PROPERTIES OF SATURATED FREON 113 (CCl2F - CClF2)
LIQUID DENSITY X 10' (LBM/FT3)
LIQUID THERMAL CONDUCTIVITY x 10⁴ (BTU/HR-FT-°F)
LIQUID VISCOSITY X 10⁶ (LBM/FT-SEC)
SATURATION PRESSURE X 10⁰ (PSIA)
VAPOR DENSITY X 10² LBM/FT³
SURFACE TENSION X 10⁴ (LBF/FT)
VAPOR VISCOSITY X 10⁶ (LBM/FT-SEC)
LATENT HEAT OF VAPORIZATION X 10⁻¹ (BTU/LBM)
FREEZING POINT ~ -31°F
CRITICAL POINT ~ 417°F ~ 495 PSIA
TEMPERATURE ~ °F
-100 -50 0 50 100 150 200 250 300 350 400 450

FLUID Ethanol

Chemical Symbol CH_3CH_2OH

Molecular Weight 46.07

Freezing Point (°F) -174

Critical Temperature (°F) 469

Critical Pressure (psia) 927

TEMP	Psat	Hfg	DENSITY				VISCOSITY				CONDUCTIVITY				SURF. TEN.		FOM
			Liquid		Vapor		Liquid		Vapor		Liquid		Vapor				
°F	psia	$\frac{B}{lb_m}$		$\frac{lb_m}{ft^3}$		$\frac{lb_m}{ft^3}$	T, °F	$\frac{lb_m}{ft\text{-}sec}$ x10[2]	T, °F	$\frac{lb_m}{ft\text{-}sec}$ x10[6]	T, °F	$\frac{B}{h\text{-}ft\text{-}°F}$	T, °F	$\frac{B}{h\text{-}ft\text{-}°F}$	T, °F	x10[4] $\frac{lb_f}{ft}$	
													20	.0071			
											30	.107	40	.0075			
50	.44	389		49.8		.003		.097		6.05	50	.106	60	.0079	50	16.17	
											100	.104	100	.0089			
150	8.5	370		46.7		.06		.037		6.72	150	.102			150	12.74	
200	24.6	355		45.1		.175		.024		7.39	180	.101			200	11.03	
250	63.9	327		43.2		.421		.016							250	9.25	
300	137	291		40.6		.910		.011		8.06					300	7.40	
Refer	G3	G3		G3		G3		G3		G3		G9		G5		G3	

FLUID Propane

Chemical Symbol C_3H_8

Molecular Weight 44.09

Freezing Point (°F) -305.9

Critical Temperature (°F) 206.2

Critical Pressure (psia) 618

TEMP	Psat	Hfg	DENSITY				VISCOSITY				CONDUCTIVITY				SURF. TEN.		FOM
			Liquid		Vapor		Liquid		Vapor		Liquid		Vapor				
°F	psia	B/lbm		lbm/ft³		lbm/ft³	T, °F	lbm/ft-sec x10²	T, °F	lbm/ft-sec x10⁶	T, °F	B/h-ft-°F	T, °F	B/h-ft-°F	T, °F	x10⁴ lbf/ft	
-150	.4																
-100	3.0																
- 50	12.9												-40	.0067			
0	39.0												0	.0078			
20	55.5	166.3		33.67		.526		.0093		4.84		.0555	20	.0084	20	8.91	
40	78.0	160.3		32.73		.730		.0081		5.04		.0535	40	.0090	40	7.40	
60	107.1	152.6		31.75		.990		.0071		5.31		.0514	60	.0096	60	6.03	
													80	.0103			
100	187.0	135.6		29.58		1.69		.0056		5.64		.0474	100	.0110	100	3.36	
													120	.0117			
140	305.0	112.5		27.00		2.78		.0043		6.05		.0437			120	1.44	
													200	.0147			
Refer	G3	G3		G3		G3		G3		G3		G12		G5		G3	

FLUID Nitrogen

Chemical Symbol N_2

Molecular Weight 28.02

Freezing Point (°F) -345.8

Critical Temperature (°F) -232.87

Critical Pressure (psia) 492.45

TEMP	P_{sat}	Hfg	DENSITY				VISCOSITY				CONDUCTIVITY				SURF. TEN.		FOM
			Liquid		Vapor		Liquid		Vapor		Liquid		Vapor				
°F	psia	$\frac{B}{lb_m}$		$\frac{lb_m}{ft^3}$		$\frac{lb_m}{ft^3}$	T, °F	$\frac{lb_m}{ft\text{-}sec} \times 10^2$	T, °F	$\frac{lb_m}{ft\text{-}sec} \times 10^6$	T, °F	$\frac{B}{h\text{-}ft\text{-}°F}$	T, °F	$\frac{B}{h\text{-}ft\text{-}°F}$	T, °F	$\frac{lb_f}{ft} \times 10^4$	
-345.8	1.91							.0202				.0915			125	7.30	
-340	3.23							.0171		3.09		.0887			135	6.44	
-320	15.4	85.1		50.38		.288		.0104		3.63		.0800		.0050	145	5.58	
-300	47.0	78.8		47.17		.842		.0074		4.17		.0714		.0062	150	5.18	
-280	113.1	69.1		43.18		1.97		.0057		4.64		.0626		.0084			
-260	226.2	56.0		38.40		4.17		.0050		5.11		.0537		.0127			
-240	409.8	33.7		30.88		9.26				5.64				.0260			
-232.9	492.4	0		19.64		19.64				5.78					-232.9	0	
Refer	G12	G12		G12		G12		G12		G12		G12		G12	G12	G12	

H. Spaceborne Heat Pipes

Heat pipes have been flown on three satellites to date. Details of these pipes can be found on the following data sheets. In addition, four other systems (listed below) will be flown in the near future.

1. The OSO-G spacecraft will employ a system of circular heat pipes to form an "isothermal" platform for the PAC experiment.

2. OAO spacecraft will use circular heat pipes for isothermalization of part of the structure.

3. A controllable heat pipe flight experiment will be flown on the OAO-C spacecraft.

4. The ATS F&G spacecraft will use heat pipe networks for temperature control.

SPACEBORNE HEAT PIPES

VEHICLE (Launch Date)	Agena for ATS-A (April 5, 1967)	ATS-E (Mid 1969)	GEOS-B (Jan. 11, 1968)
NUMBER Of HEAT PIPES	1	8	2
HEAT PIPE TEMP. (^{o}F)	$\sim$190	20 to 90 (nom)	$\sim$60
MAX. TRANSFER/PIPE (w)	10	60	
FLUID	H_2O (7.5 gr)	NH_3	Freon-11
TUBE — Material	347 SS	Alum. extrusion	
TUBE — OD-Length	.75" - 12.1"	.42"ID - 14.4 ft.	2" - 20", 36"
TUBE — Wall Thick.	.035"	.030"	
WICK — Material	100 mesh SS screen,	105-200 SS screen	Alum. mesh
WICK — Type	3 layers with helical spring	Artery - .090" ID +2 layers on wall	
HEAT PIPE DESCRIPTION	Evaporator - 2.5", Radiation condenser Uniform wick	Non-continuous, circumferential- embedded in .5" honeycomb	
HEAT PIPE WEIGHT (#)		4.4 ea. (35 tot)	
LIFE (yrs.) — Design		3	
LIFE (yrs.) — Actual	> 51 hours	$\sim$	> 5 months
FABRICATOR	Los Alamos	D. W. Douglas Labs (Mac DAC)	Applied Physics Lab
HEAT PIPE FUNCTION	Experiment	Increase Solar cell eff. (+20%) by decreasing T max.	Smooth temp. excursions of two transponders
PERFORMANCE — Design		60W/pipe, minimal ΔT	
PERFORMANCE — Actual	$\pm$ 2°C for 14 orbits (51 hours)	400W/pipe, $\pm$ 5°F (except He gas) in lab-no flight data.	$\pm$3°F on heat pipe wall
REFERENCE	H1	H2	H3
COMMENTS	X-mtr power supply too low for x-mission at 51 hrs. Some non-condensible gas in pipe.	Inert gas (he) added to ease frozen start-up. Satellite failed to stabilize in orbit.	Big drop across evaporator and condenser mentioned, no numbers. (GEOS-B also called Explorer XXXVI)

I. Boilers/Sublimators

I. Purpose: Boilers and sublimators reject heat to space by vaporizing fluid (from the liquid and solid states respectively) and dispelling it from the spacecraft. Because the fluid is non-recoverable, this control technique should be considered for short-term use only.

II. Discussion: Boilers and sublimators have been employed for contingency cooling on short duration manned missions. The maximum heat rejection is directly proportional to the weight of expendable coolant available and hence, it is impractical to design these units for continuous use on long term flights.

The BIOS satellite incorporated a water boiler into its environmental control system to augment radiator heat rejection (Reference I1). Coolanol 25 was circulated through a space radiator and its outlet temperature was sensed. When this temperature reached 40°F, the boiler was activated to remove additional heat from the fluid. Operation continued until the outlet temperature reached 34°F. The unit worked well during thermal vacuum testing but was not needed during the nine day flight.

Sublimators have been used in the LEM environmental control system, the Instrument Unit Systems of the Saturn IB and V, and the Apollo Space Suite Back Pack.

These units have been of the porous plate design, in which the liquid (water) is drawn into the plate by capillary force and freezes. Vapor sublimates from the space-facing side of the ice slug and removes heat from the plate.

No data sheet was filled out for these elements because available information was not sufficient to define the system configurations and operating characteristics.

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CONVERSIONS

Conversions

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LISTING BY PHYSICAL QUANTITY

ACCELERATION

foot/second^2	meter/second^2	−01 3.048*
free fall, standard	meter/second^2	+00 9.80665*
gal	meter/second^2	−02 1.00*
inch/second^2	meter/second^2	−02 2.54*

AREA

acre	meter^2	+03 4.0468564224*
are	meter^2	+02 1.00*
barn	meter^2	−28 1.00*
circular mil	meter^2	−10 5.0670748
foot^2	meter^2	−02 9.290304*
hectare	meter^2	+04 1.00*
inch^2	meter^2	−04 6.4516*
mile^2 (U.S. statute)	meter^2	+06 2.589988110336*
section	meter^2	+06 2.589988110336*
township	meter^2	+07 9.3239572
yard^2	meter^2	−01 8.3612736*

DENSITY

gram/centimeter^3	kilogram/meter^3	+03 1.00*
lbm/inch^3	kilogram/meter^3	+04 2.7679905
lbm/foot^3	kilogram/meter^3	+01 1.6018463
slug/foot^3	kilogram/meter^3	+02 5.15379

ELECTRICAL

abampere	ampere	+01 1.00*
ampere (international of 1948)	ampere	−01 9.99835

To convert from	*to*	*multiply by*
statampere	ampere	−10 3.335640
gilbert	ampere turn	−01 7.9577472
oersted	ampere/meter	+01 7.9577472
abcoulomb	coulomb	+01 1.00*
ampere hour	coulomb	+03 3.60*
coulomb (international of 1948)	coulomb	−01 9.99835
faraday (based on carbon 12)	coulomb	+04 9.64870
faraday (chemical)	coulomb	+04 9.64957
faraday (physical)	coulomb	+04 9.65219
statcoulomb	coulomb	−10 3.335640
abfarad	farad	+09 1.00*
farad (international of 1948)	farad	−01 9.99505
statfarad	farad	−12 1.112650
abhenry	henry	−09 1.00*
henry (international of 1948)	henry	+00 1.000495
stathenry	henry	+11 8.987554
abmho	mho	+09 1.00*
statmho	mho	−12 1.112650
abohm	ohm	−09 1.00*
ohm (international of 1948)	ohm	+00 1.000495
statohm	ohm	+11 8.987554
gamma	tesla	−09 1.00*
gauss	tesla	−04 1.00*
abvolt	volt	−08 1.00*
statvolt	volt	+02 2.997925
volt (international of 1948)	volt	+00 1.000330
maxwell	weber	−08 1.00*
unit pole	weber	−07 1.256637

ENERGY

British thermal unit (International Steam Table)	joule	+03 1.05504
British thermal unit (mean)	joule	+03 1.05587
British thermal unit (thermochemical)	joule	+03 1.054350264488888
British thermal unit (39° F)	joule	+03 1.05967
British thermal unit (60° F)	joule	+03 1.05468
calorie (International Steam Table)	joule	+00 4.1868
calorie (mean)	joule	+00 4.19002
calorie (thermochemical)	joule	+00 4.184*
calorie (15° C)	joule	+00 4.18580
calorie (20° C)	joule	+00 4.18190
calorie (kilogram, International Steam Table)	joule	+03 4.1868

To convert from	*to*	*multiply by*
calorie (kilogram, mean)	joule	+03 4.19002
calorie (kilogram, thermochemical)	joule	+03 4.184*
electron volt	joule	−19 1.60210
erg	joule	−07 1.00*
foot lbf	joule	+00 1.3558179
foot poundal	joule	−02 4.2140110
joule (international of 1948)	joule	+00 1.000165
kilocalorie (International Steam Table)	joule	+03 4.1868
kilocalorie (mean)	joule	+03 4.19002
kilocalorie (thermochemical)	joule	+03 4.184*
kilowatt hour	joule	+06 3.60*
kilowatt hour (international of 1948)	joule	+06 3.60059
ton (nuclear equivalent of TNT)	joule	+09 4.20
watt hour	joule	+03 3.60*

ENERGY/AREA TIME

Btu (thermochemical)/foot² second	watt/meter²	+04 1.1348931
Btu (thermochemical)/foot² minute	watt/meter²	+02 1.8914885
Btu (thermochemical)/foot² hour	watt/meter²	+00 3.1524808
Btu (thermochemical)/inch² second	watt/meter²	+06 1.6342462
calorie (thermochemical)/cm² minute	watt/meter²	+02 6.9733333
erg/centimeter² second	watt/meter²	−03 1.00*
watt/centimeter²	watt/meter²	+04 1.00*

FORCE

dyne	newton	−05 1.00*
kilogram force, kgf	newton	+00 9.80665*
kilopond force	newton	+00 9.80665*
kip	newton	+03 4.4482216152605*
lbf (pound force, avoirdupois)	newton	+00 4.4482216152605*
ounce force (avoirdupois)	newton	−01 2.7801385
pound force, lbf (avoirdupois)	newton	+00 4.4482216152605*
poundal	newton	−01 1.38254954376*

LENGTH

angstrom	meter	−10 1.00*
astronomical unit	meter	+11 1.49598
cable	meter	+02 2.19456*
caliber	meter	−04 2.54*
chain (surveyor or gunter)	meter	+01 2.01168*
chain (engineer or ramden)	meter	+01 3.048*
cubit	meter	−01 4.572*
fathom	meter	+00 1.8288*
fermi	meter	−15 1.00*

To convert from	*to*	*multiply by*
foot	meter	−01 3.048*
foot (U.S. survey)	meter	+00 1200/3937*
foot (U.S. survey)	meter	−01 3.048006096
furlong	meter	+02 2.01168*
hand	meter	−01 1.016*
inch	meter	−02 2.54*
league (British nautical)	meter	+03 5.559552*
league (international nautical)	meter	+03 5.556*
league (statute)	meter	+03 4.828032*
light year	meter	+15 9.46055
link (engineer or ramden)	meter	−01 3.048*
link (surveyor or gunter)	meter	−01 2.01168*
meter	wavelengths Kr 86	+06 1.65076373*
micron	meter	−06 1.00*
mil	meter	−05 2.54*
mile (U.S. statute)	meter	+03 1.609344*
mile (British nautical)	meter	+03 1.853184*
mile (international nautical)	meter	+03 1.852*
mile (U.S. nautical)	meter	+03 1.852*
nautical mile (British)	meter	+03 1.853184*
nautical mile (international)	meter	+03 1.852*
nautical mile (U.S.)	meter	+03 1.852*
pace	meter	−01 7.62*
parsec	meter	+16 3.08374
perch	meter	+00 5.0292*
pica (printers)	meter	−03 4.2175176*
point (printers)	meter	−04 3.514598*
pole	meter	+00 5.0292*
rod	meter	+00 5.0292*
skein	meter	+02 1.09728*
span	meter	−01 2.286*
statute mile	meter	+03 1.609344*
yard	meter	−01 9.144*

MASS

carat (metric)	kilogram	−04 2.00*
dram (avoirdupois)	kilogram	−03 1.7718451953125*
dram (troy or apothecary)	kilogram	−03 3.8879346*
grain	kilogram	−05 6.479891*
gram	kilogram	−03 1.00*
hundredweight (long)	kilogram	+01 5.080234544*
hundredweight (short)	kilogram	+01 4.5359237*
kgf second^2 meter (mass)	kilogram	+00 9.80665*
kilogram mass	kilogram	+00 1.00*
lbm (pound mass, avoirdupois)	kilogram	−01 4.5359237*

To convert from	*to*	*multiply by*
ounce mass (avoirdupois)	kilogram	−02 2.8349523125*
ounce mass (troy or apothecary)	kilogram	−02 3.11034768*
pennyweight	kilogram	−03 1.55517384*
pound mass, lbm (avoirdupois)	kilogram	−01 4.5359237*
pound mass (troy or apothecary)	kilogram	−01 3.732417216*
scruple (apothecary)	kilogram	−03 1.2959782*
slug	kilogram	+01 1.45939029
ton (assay)	kilogram	−02 2.9166666
ton (long)	kilogram	+03 1.0160469088*
ton (metric)	kilogram	+03 1.00*
ton (short, 2000 pound)	kilogram	+02 9.0718474*
	MISCELLANEOUS	
degree (angle)	radian	−02 1.7453292519943
grad	radian	−02 1.5707963
minute (angle)	radian	−04 2.90888208666
second (angle)	radian	−06 4.848136811
grad	degree (angular)	−01 9.00*
$foot^3$/second	$meter^3$/second	−02 2.8316846592*
$foot^3$/minute	$meter^3$/second	−04 4.7194744
Btu (thermochemical)/lbm F°	joule/kg C°	+03 4.184*
kilocalorie (thermochemical)/kg C°	joule/kg C°	+03 4.184*
Btu (thermochemical)/lbm	joule/kilogram	+03 2. 3244444
kilocalorie (thermochemical)/kilogram	joule/kilogram	+03 4.184*
rad (radiation dose absorbed)	joule/kilogram	−02 1.00*
roentgen	coulomb/kilogram	−04 2.57976*
curie	disintegration/second	+10 3.70*
kayser	1/meter	+02 1.00*
denier (international)	kilogram/meter	−07 1.00*
	POWER	
Btu (thermochemical)/second	watt	+03 1.054350264488888
Btu (thermochemical)/minute	watt	+01 1.7572504
calorie (thermochemical)/second	watt	+00 4.184*
calorie (thermochemical)/minute	watt	−02 6.9733333
foot lbf/hour	watt	−04 3.7661610
foot lbf/minute	watt	−02 2.2596966
foot lbf/second	watt	+00 1.3558179
horsepower (550 foot lbf/second)	watt	+02 7.4569987
horsepower (boiler)	watt	+03 9.80950
horsepower (electric)	watt	+02 7.46*
horsepower (metric)	watt	+02 7.35499
horsepower (water)	watt	+02 7.46043
kilocalorie (thermochemical)/minute	watt	+01 6.9733333
kilocalorie (thermochemical)/second	watt	+03 4.184*
watt (international of 1948)	watt	+00 1.000165

To convert from	*to*	*multiply by*
	PRESSURE	
atmosphere	newton/meter^2	+05 1.01325*
bar	newton/meter^2	+05 1.00*
barye	newton/meter^2	−01 1.00*
centimeter of mercury (0° C)	newton/meter^2	+03 1.33322
centimeter of water (4° C)	newton/meter^2	+01 9.80638
dyne/centimeter^2	newton/meter^2	−01 1.00*
foot of water (39.2° F)	newton/meter^2	+03 2.98898
inch of mercury (32° F)	newton/meter^2	+03 3.386389
inch of mercury (60° F)	newton/meter^2	+03 3.37685
inch of water (39.2° F)	newton/meter^2	+02 2.49082
inch of water (60° F)	newton/meter^2	+02 2.4884
kgf/centimeter^2	newton/meter^2	+04 9.80665*
kgf/meter^2	newton/meter^2	+00 9.80665*
lbf/foot^2	newton/meter^2	+01 4.7880258
lbf/inch^2 (psi)	newton/meter^2	+03 6.8947572
millibar	newton/meter^2	+02 1.00*
millimeter of mercury (0° C)	newton/meter^2	+02 1.333224
pascal	newton/meter^2	+00 1.00*
psi (lbf/inch^2)	newton/meter^2	+03 6.8947572
torr (0° C)	newton/meter^2	+02 1.33322
	SPEED	
foot/hour	meter/second	−05 8.4666666
foot/minute	meter/second	−03 5.08*
foot/second	meter/second	−01 3.048*
inch/second	meter/second	−02 2.54*
kilometer/hour	meter/second	−01 2.7777778
knot (international)	meter/second	−01 5.144444444
mile/hour (U.S. statute)	meter/second	−01 4.4704*
mile/minute (U.S. statute)	meter/second	+01 2.68224*
mile/second (U.S. statute)	meter/second	+03 1.609344*
	TEMPERATURE	
Celsius (temperature)	Kelvin	K=C+273.15
Fahrenheit (temperature)	Kelvin	K=(5/9) (F+459.67)
Rankine (temperature)	Kelvin	K=(5/9)R
Fahrenheit (temperature)	Celsius	C=(5/9) (F−32)
Kelvin (temperature)	Celsius	C=K−273.15
	THERMAL CONDUCTIVITY	
Btu inch/foot^2 second F°	joule/meter sec K°	+02 5.1887315

To convert from	*to*	*multiply by*
	TIME	
day (mean solar)	second (mean solar)	+04 8.64*
day (sidereal)	second (mean solar)	+04 8.6164090
hour (mean solar)	second (mean solar)	+03 3.60*
hour (sidereal)	second (mean solar)	+03 3.5901704
minute (mean solar)	second (mean solar)	+01 6.00*
minute (sidereal)	second (mean solar)	+01 5.9836174
month (mean calendar)	second (mean solar)	+06 2.628*
second (mean solar)	second (ephemeris)	Consult American Ephemeris and Nautical Almanac
second (sidereal)	second (mean solar)	−01 9.9726957
tropical year 1900, Jan., day 0, hour 12	second (ephemeris)	+07 3.15569259747*
year (calendar)	second (mean solar)	+07 3.1536*
year (sidereal)	second (mean solar)	+07 3.1558150
year (tropical)	second (mean solar)	+07 3.1556926
year 1900, tropical, Jan., day 0, hour 12	second (ephemeris)	+07 3.15569259747*
	VISCOSITY	
centistoke	meter²/second	−06 1.00*
stoke	meter²/second	−04 1.00*
foot²/second	meter²/second	−02 9.290304*
centipoise	newton second/meter²	−03 1.00*
lbm/foot second	newton second/meter²	+00 1.4881639
lbf second/foot²	newton second/meter²	+01 4.7880258
poise	newton second/meter²	−01 1.00*
poundal second/foot²	newton second/meter²	+00 1.4881639
slug/foot second	newton second/meter²	+01 4.7880258
rhe	meter²/newton second	+01 1.00*
	VOLUME	
acre foot	meter³	+03 1.2334819
board foot	meter³	−03 2.359737216*
bushel (U.S.)	meter³	−02 3.523907016688*
cord	meter³	+00 3.6245563
cup	meter³	−04 2.365882365*
dram (U.S. fluid)	meter³	−06 3.6966911953125*
fluid ounce (U.S.)	meter³	−05 2.95735295625*
foot³	meter³	−02 2.8316846592*
gallon (British)	meter³	−03 4.546087
gallon (U.S. dry)	meter³	−03 4.40488377086*
gallon (U.S. liquid)	meter³	−03 3.785411784*
gill (British)	meter³	−04 1.420652
gill (U.S.)	meter³	−04 1.1829412
hogshead (U.S.)	meter³	−01 2.38480942392*

To convert from	*to*	*multiply by*
$inch^3$	$meter^3$	−05 1.6387064*
liter	$meter^3$	−03 1.00*
ounce (U.S. fluid)	$meter^3$	−05 2.95735295625*
peck (U.S.)	$meter^3$	−03 8.80976754172*
pint (U.S. dry)	$meter^3$	−04 5.506104713575*
pint (U.S. liquid)	$meter^3$	−04 4.73176473*
quart (U.S. dry)	$meter^3$	−03 1.101220942715*
quart (U.S. liquid)	$meter^3$	−04 9.4635295
stere	$meter^3$	+00 1.00*
tablespoon	$meter^3$	−05 1.478676478125*
teaspoon	$meter^3$	−06 4.92892159375*
ton (register)	$meter^3$	+00 2.8316846592*
$yard^3$	$meter^3$	−01 7.64554857984*